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Environmental Research and Technology, Inc.
Concord, MA

Prepared for

Environmental Protection Agency
Research Triangle Park, NC

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Through a supplementary control system (SCS), SO_2 emissions from a facility are temporarily curtailed when meteorological conditions conducive to high ambient SO_2 concentrations exist or are anticipated. This report describes a case study demonstration of SCS reliability analysis techniques presented in "Technique for Supplementary Control System Reliability Analysis and Upgrading" (EPA-450/2-76-015). A user manual is also provided. A primary objective of this study is to discuss the reliability analysis techniques and their applicability to the problem of estimating SCS reliability.

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1. INTRODUCTION

1.1 Overview and Objectives

This report was prepared by Environmental Research & Technology, Inc. (ERT) under Environmental Protection Agency (EPA) Contract 68-02-2090. It follows an earlier research program performed by ERT (EPA Contract 68-02-1342) in which analytical tools were developed specifically for evaluating the effectiveness of Supplementary Control Systems (SCS) in meeting ambient air quality standards (EPA 1976a).

The present study applies those analytical tools to a case study of an operational SCS. A user manual (Appendix B) is also provided. The SCS at the Commonwealth Edison Kincaid Station at Kincaid, Illinois, was chosen.* It was operational as of July 1976. However, neither of the two 600-Mw generation units at Kincaid was operational until October 1976. The 123-day period October 1, 1976, through January 31, 1977, was used in this analysis. A 120-day test period is the minimum required to assess the reliability analysis techniques (EPA 1976b).

A primary objective of this study is to discuss the analytical techniques themselves and their applicability to the problem of estimating SCS reliability. By reviewing in detail a case study demonstration of the analysis, a more complete understanding of the usefulness and appropriateness of these techniques has been obtained.

All the objectives of this study are summarized below.

- Select an SCS for use in the case study analysis and obtain permission for the use of the data from this SCS.
- Define the air quality forecasting system to be used in the operation of the case study SCS.
- During 120 days of SCS operations, collect all pertinent data required for reliability analysis.
- Test the reliability of the SCS through application of error ratios as defined in the previous work.

---

*Although EPA has approved SCS for certain SO_2 sources, SCS is not approved as a control strategy for the Kincaid Station. It is referred to here only for case study purposes.

- Apply the ERT computer program PROBL to the evaluation of the 120-day test period.
- Document the model PROBL and provide a user manual.
- Evaluate the analytical techniques and their usefulness.

It is important to clarify the intended meaning of the word "reliability". The ultimate reliability of an SCS program is measured in terms of whether or not the applicable standards have been violated. The applicable standards for the Kincaid SCS are the National Ambient Air Quality Standards (NAAQS) for sulfur dioxide (SO_2), which specify 3- and 24-hour average concentrations that can be exceeded no more than once per year. Because no excesses of the NAAQS were observed during the 123-day test period, the reliability of the Kincaid SCS has to be evaluated in other terms.

A second definition of "reliability" for an SCS is the consistent ability to predict ground-level concentrations accurately. This definition is a more stringent reliability requirement and represents the primary focus of this case study.

1.2 SCS Reliability Analysis

ERT developed procedures for evaluating the uncertainty of meteorological forecasting, emissions forecasting and air quality modeling associated with the operation of an SCS. The procedures require that the following four concentration values be recorded for each forecasting time:

- the concentration predicted by a model using predicted meteorological parameters and predicted emissions (this concentration value is the basis of the real-time SCS control action);
- the concentration predicted by a model using observed meteorological parameters and predicted emissions;
- the concentration predicted by a model using observed meteorological parameters and observed emissions and
- the maximum concentration recorded by the monitoring network.

The procedure combines the above recorded data and model results to attempt to isolate the errors due to meteorological forecasting uncertainty from the errors due to model uncertainty.

The observed maximum concentration C_o is represented by $C_o = Q \cdot M$, where Q is the emission rate and M is a function of the dispersion-related meteorology.

The predicted maximum concentration is assumed to be $C_p = Q \cdot M \cdot R_T$, where R_T is a ratio describing the total error between predicted and observed concentrations, that is:

$$R_T = C_p/C_o.$$

R_T contains contributions from many sources of error and uncertainty. These sources of uncertainty arise from each component of the SCS - meteorological forecasting, emissions forecasting and air quality modeling.

Consider the following formulation of R_T:

$$R_T = R_w \cdot R_q \cdot R_m$$

where R_w, R_q and R_m are the error ratios for meteorological forecasting (w = weather), emissions predictions (q = emissions) and air quality modeling (m = model), respectively.

While the multiplication of the three error ratios above does not define all the potential errors within an SCS, it does relate to all errors made in evaluating the predicted concentration (C_p) versus the measured concentrations (C_o) in the field. The uncertainty involved in the actual measurement of concentrations surrounding the source is omitted from this particular consideration. Aside from the obvious instrumentation errors in measuring concentrations, there is the additional difficulty of not having measurements of concentrations at each desirable point. The theoretically appropriate system would have measured the maximum concentration at any receptor point in the area of the source. Because the monitors measure only a fraction of the occurrences of significant ground-level concentrations, the analysis techniques must be interpreted in light of that difficulty.

This study has defined seven specific sets of data hours, called cases, in which comparisons of predicted versus measured concentrations are made. The specification of these cases is detailed in Section 3.2. The results obtained in each of the seven cases will lead to a more complete understanding of the operational SCS than would a single error ratio analysis for all hours.

Another analysis technique used does not deal with the errors involved in forecasting methods but rather with the ability of the SCS to ensure that NAAQS are not exceeded. In general, this can be analyzed by developing a probability distribution of concentrations. The probability distribution of the observed maximum concentration around an uncontrolled source may be defined as the combined probability of the emissions Q and the meteorology M as defined in the equation for C_o above. If it is assumed that Q and M are independent, the analysis is fairly straightforward. Note, however, that for nonbase-loaded plants, Q and M may not be independent. Peak loads tend to occur with very cold winter storms and hot summer afternoons, while nighttime stable atmospheres are associated with generally light loads.

With an operational SCS the probability of expected ground-level concentrations is the combined probabilities of Q, M, and R_T, the SCS total error ratio. The air quality impact of a given meteorological situation is dependent on the emissions, which are linked to the meteorology through the application of controls. There is a probable interdependence of emissions and meteorology, but the present analysis will assume their independence. Combining probabilities has been automated in a computer program called PROBL. PROBL calculates the probability of exceeding the ambient air quality standard for various control strategies, thereby providing a major test of the reliability of an SCS as a function of control strategy.

1.3 Kincaid SCS Program

The SCS of the Commonwealth Edison Kincaid station was selected as a test example and permission to use the data was obtained. Because ERT was responsible for providing the meteorological and air quality forecasting, air quality monitoring, and air quality and emission control decision modeling, using the Kincaid program was a cost-effective way of completing the case study of reliability. The SCS program at Kincaid became operational on July 19, 1976 and produced 123 days (months of October, November, December and January) of operational SCS data by January 31, 1977.

The Kincaid Generating Station is located approximately 25 km southeast of Springfield, Illinois, and consists of two adjacent 600-Mw coal-fired generating units. ERT is under contract to the operator of Kincaid, Commonwealth Edison Company, to provide nearly all of the SCS program operations. Important features of the program are:

- a 10-station network of monitors for SO_2 (the pollutant being controlled);
- the communications network to collect real-time concentration and meteorological information for the SCS;
- the meteorological forecasting and support to provide predictions of meteorological conditions;
- air quality modeling to predict the expected concentrations, not only at the 10 monitor locations, but also at 246 other model receptor locations spaced around the generating station;
- a control system for evaluating the threshold concentrations at which emission cutbacks should be initiated and the delivery system for cutback recommendations and
- data retrieval, storage and validation systems to ensure the accuracy of the monitored data collected and its retention for future analysis.

The use of Kincaid, where ERT operates the SCS, has greatly facilitated the collection and processing of data. Greater difficulties would have been experienced if another SCS with a different operator had been used in the analysis.

There is, however, one significant drawback to the use of the Kincaid SCS system in this case study. Over the four-month period, October through January, only two control actions were initiated and no violations of the standards were recorded. Because of this very low number of control actions, the case study method will not effectively test the response of a control system to predicted excursions above the standards, nor will it provide information on the establishment of the threshold for initiating control actions. Although recommendations will be made on the basis of the analysis of the four-month data record, the system has not been "put to the test" often enough to evaluate its response. In spite of this drawback, the case study will provide much information on the reliability analysis technique and its applicability to operational situations.

1.4 Detailed Discussion of the Kincaid SCS

ERT is operating the SCS for Commonwealth Edison Company for the purpose of maintaining NAAQS for SO_2 in the area of the Kincaid Generating Station in central Illinois. The Kincaid Station consists of two 600-Mw-rated generating units that exhaust through two side-by-side 500-ft stacks. The approximate separation distance between the two stacks is 100 feet. The close proximity of the two stacks has led to the reasonable assumption in model evaluations that the stacks are, for diffusion purposes, a single point source. In addition, it is assumed as a matter of conservative modeling practice that plume rise is not enhanced by the interaction of the two plumes.

The Kincaid Station is a mine-mouth coal-fired plant that burns approximately 4.2% sulfur coal. When burned, this fuel produces emissions on the order of 5840 g/sec for each unit when operated at capacity. Model calculations at capacity indicate that over a three-year period, ground-level concentrations could approach the 24-hour average standard of 365 $\mu g/m^3$ (0.14 ppm) of SO_2 on 22 days (ERT 1976). The maximum ground-level concentrations were normally expected in the 6 to 8 km distance from the source but could occur as far as 17 kilometers out. No occurrences of 3-hour average or annual average concentrations above the respective standards were expected based on preliminary modeling results.

A real-time air monitoring (AIRMAP) network in the vicinity of the Kincaid Generating Station measures SO_2, meteorological and power plant parameters. The location of the 10 monitoring stations [the required number - (EPA 1976)] and the Kincaid Generating Station are shown in Figure 1-1. The grid of 256 receptor points used in the Kincaid AQFOR-CONDEC Model is displayed in Figure 1-2. Table 1-1 presents information on the monitoring stations in the network.

SO_2 concentrations are monitored by Meloy flame photometric analyzers at all 10 monitoring stations. Commonwealth Edison operates a 76 meter (250-foot) tower, which is maintained by Murray and Trettel, Inc. and contains instrumentation for wind speed and wind direction at the 10 meter (33-foot) and 61 meter (200-foot) levels of the tower. The temperature difference (ΔT) between the 10 meter and 61 meter level is also measured. Low-level atmospheric stability is determined from the ΔT between these two levels. Dew point and insolation are measured at the 2 meter level of the tower. The data obtained from the SO_2 sensors and these tower sensors are transmitted in real-time to the SCS control center in Concord, Massachusetts. Strip charts serve as a backup for the real-time data acquisition system.

Table 1-2 presents the operating experience of each of the Kincaid generating units during the 123-day test period. Both units operated simultaneously for 19 days, mostly in January, which represents 16% of the test period.

Table 1-3 presents raw real-time data capture statistics by site for all SCS parameters over the 123-day test period. Raw real-time data capture is defined as the percentage of data received in real-time via computer, without review by data analysts or meteorologists for validity or historical data processing.

A monostatic acoustic sounder manufactured by Aerovironment is operated by ERT to obtain real-time information on the height of temperature discontinuities in the vertical (inversions) that may exist. A remote readout of the instrument output is displayed in real-time at the SCS control center for use by the SCS forecasters.

The air quality dispersion model that is used in the real-time SCS program is called the Kincaid AQFOR-CONDEC model (details in Appendix A). This model calculates the expected ground-level concentrations around the Kincaid Station (AQFOR portion) and selects a plant operating schedule from a specified set of emission control actions (CONDEC portion).

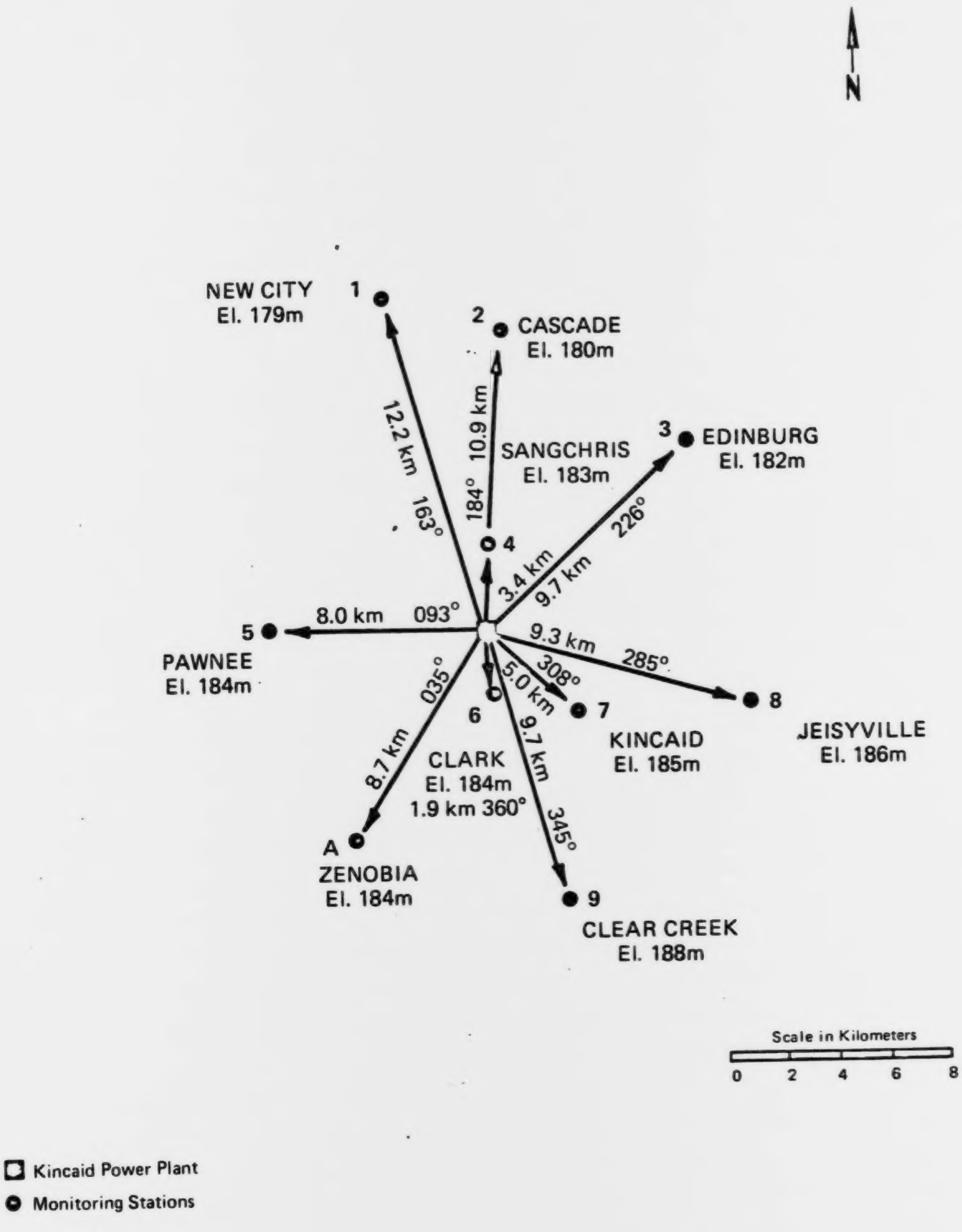

N
NEW CITY
El. 179m
1
2
CASCADE
El. 180m
12.2 km
10.9 km
SANGCHRIS
El. 183m
3
EDINBURG
El. 182m
163°
184°
226°
4
3.4 km
9.7 km
5
8.0 km
093°
9.3 km
285°
PAWNEE
El. 184m
035°
5.0 km
308°
7
8
6
9.7 km
KINCAID
El. 185m
JEISYVILLE
El. 186m
8.7 km
CLARK
El. 184m
1.9 km 360°
345°
A
ZENOBIA
El. 184m
9
CLEAR CREEK
El. 188m
Scale in Kilometers
0
2
4
6
8
Kincaid Power Plant
Monitoring Stations

Figure 1-1 Field Monitoring Network for the Kincaid Area

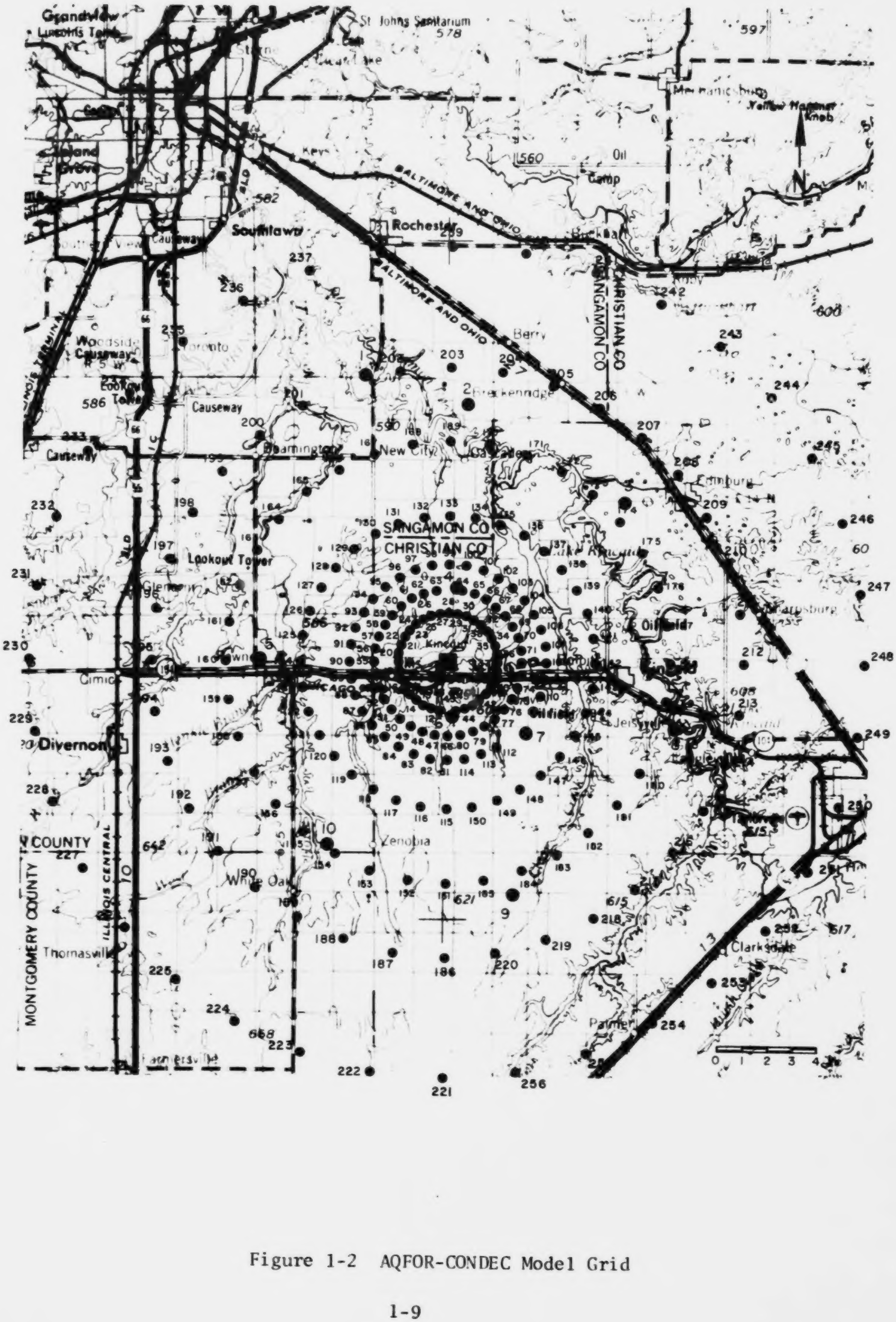

Grandview
St Johns Sanitarium
Mechanicsburg
Yellow Hammer Knob
BALTIMORE AND OHIO
Rochester
Southlawn
Causeway
Woodside
Lookout Tower
Berry
Breckenridge
SANGAMON CO
CHRISTIAN CO
New City
Kincaid
Edinburg
Oilfield
Divernon
Zenobia
White Oak
Thomasville
MONTGOMERY COUNTY
ILLINOIS CENTRAL
Clarksdale
Palmer
Farmersville
0 1 2 3 4

Figure 1-2 AQFOR-CONDEC Model Grid

TABLE 1-1

KINCAID MONITORING NETWORK INFORMATION

Station Name	Station Number	Station Elevation (m (ft) above msl[a])	Sensors	Distance kilometers (mi) from Kincaid Plant	Downwind Sector (°) from Kincaid Plant	Downwind Direction (°)[b]
New City	1	179 (587)	SO_2	12.2 (7.6)	133° - 193°	163°
Cascade	2	180 (590)	SO_2	10.9 (6.8)	154° - 214°	184°
Edinburg	3	182 (598)	SO_2	9.7 (6.0)	196° - 256°	226°
Sangchris	4	183 (599)	SO_2	3.4 (2.1)	154° - 214°	184°
Pawnee	5	184 (604)	SO_2	8.0 (5.0)	063° - 123°	093°
Pawnee Tower		184 (603)				
2m (5-ft) Level			T_d, insolation			
10m (33-ft) Level			ws, wd, T			
61m (200-ft) Level			ws, wd, ΔT, σ_θ			
Clark	6	184 (603)	SO_2	1.9 (1.2)	330° - 030°	360°
Kincaid	7	185 (606)	SO_2	5.0 (3.1)	277° - 377°	307°
Jeisyville	8	186 (610)	SO_2	9.3 (5.8)	255° - 315°	285°
Clear Creek	9	188 (618)	SO_2	9.7 (6.0)	315° - 005°	345°
Zenobia	A	184 (605)	SO_2	8.7 (5.4)	005° - 065°	035°
Power Plant		183 (602)	Acoustic sounder			
Unit 1	B	336 (1,102)[c]	Stack gas analyzer, load signal			
Unit 2	C	336 (1,102)[c]	Stack gas analyzer, load signal			

[a] msl - mean sea level

[b] The downwind direction is defined by the direction from the plant to the monitoring station. The downwind sector is subtended by an arc of ±30° centered on the downwind direction.

[c] Stack height in ft msl

TABLE 1-2

SUMMARY OF THE DAYS OF OPERATION OF THE KINCAID UNITS DURING THE 123-DAY TEST PERIOD

	Unit 1	Unit 2
October 1976	0	21
November 1976	0	20
December 1976	4	28
January 1977	28	20
Total Days	32	89
Percentage of Period	26%	72%

TABLE 1-3

KINCAID RAW REAL-TIME DATA CAPTURE FOR OCTOBER 1976 THROUGH JANUARY 1977

	Site	SCS Parameter	Data Capture (%)
B1	New City	SO_2	93.46
B2	Cascade	SO_2	99.36
B3	Edinburg	SO_2	97.53
B4	Sangchris	SO_2	98.68
B5	Pawnee	SO_2	98.54
B6	Clark	SO_2	96.24
B7	Kincaid	SO_2	97.29
B8	Jeisyville	SO_2	98.71
B9	Clear Creek	SO_2	98.78
BA	Zenobia	SO_2	98.85
BL	Pawnee Tower (Lower)	WS	99.06
BU	Pawnee Tower (Upper)	WS	99.06
BL	Pawnee Tower (Lower)	WD	99.06
BU	Pawnee Tower (Upper)	WD	99.06
BL	Pawnee Tower (Lower)	Temp.	99.06
BL	Pawnee Tower (Lower)	T_d	99.02
BU	Pawnee Tower (Upper)	ΔT	99.06
BL	Pawnee Tower (Lower)	Insolation	99.06

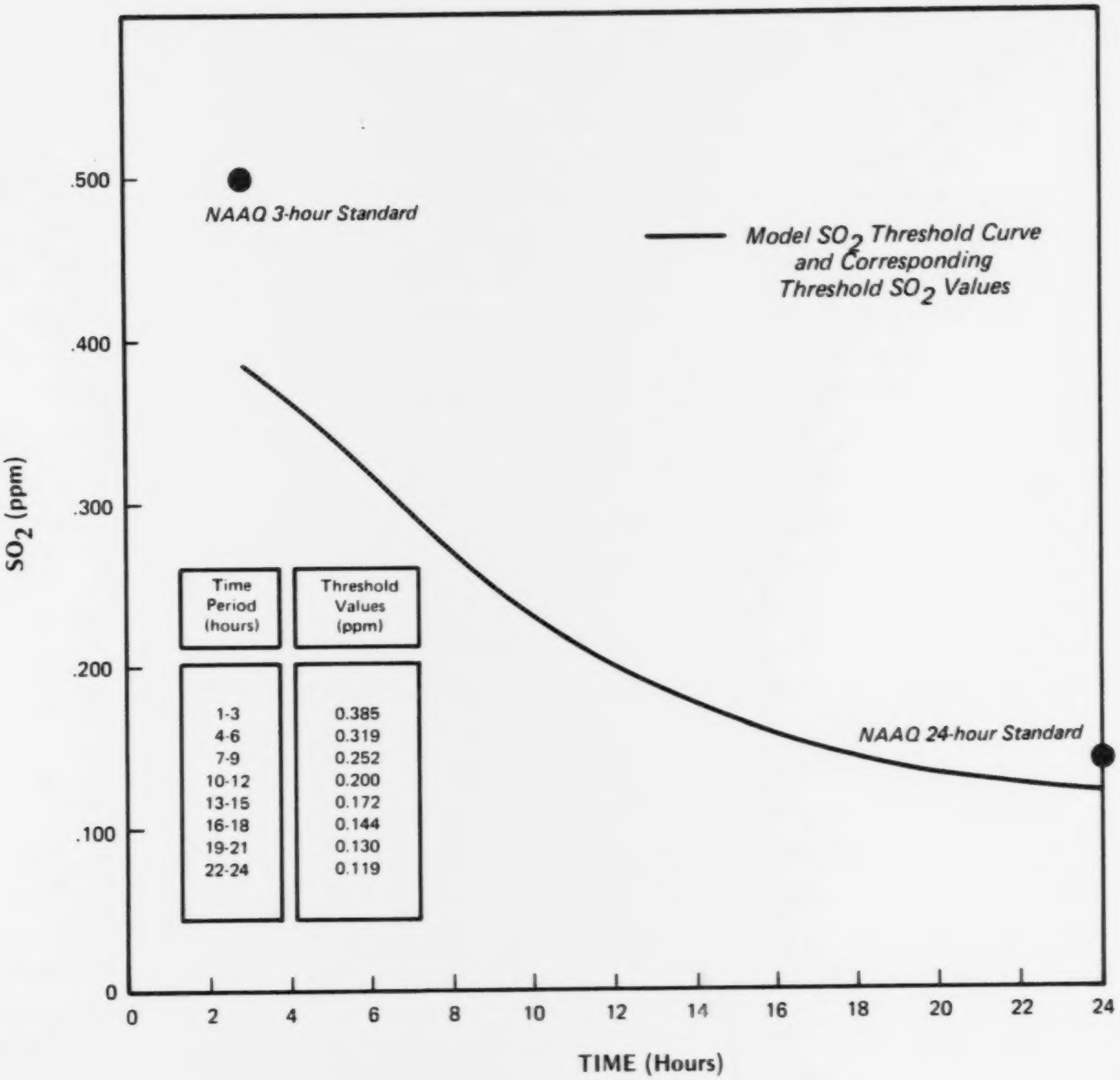
The Air Quality Forecast (AQFOR) model is a state-of-the-art multiple-source Gaussian diffusion model that has the following characteristics:

- It uses the Briggs plume rise equations but accounts for stack tip downwash where important.
- It accounts for background concentrations from a background concentration look-up table.
- It accounts for capping of the plume by an elevated inversion but considers punch through if the final plume rise is more than 50 meters above the elevated inversion height.
- The concentration is averaged over a sector width at the receptor in accordance with procedures detailed in Appendix A. A sector width of 22-1/2° has been used throughout the present analysis.

The Control Decision (CONDEC) model provides the basis for control actions, which are defined as any alterations of scheduled plant operations due to SCS recommendations. CONDEC can be initiated when scheduled plant operations and forecast meteorological conditions combine to produce predicted SO_2 concentrations that approach the NAAQS somewhere in the receptor field. Control actions can also be initiated whenever the observed SO_2 concentrations at monitor locations reach certain threshold values and the predicted meteorological conditions indicate a potential violation of the NAAQS. Predicted concentrations and guidance for control actions are obtained from the AQFOR-CONDEC computer model for the Kincaid SCS program, which computes maximum hourly SO_2 concentrations for 24 1-hour periods and compares the predicted concentrations against the model threshold values. The model first analyzes the long-term averages (that is, the 24-hour average), then continues to analyze to the shortest term average (that is, the 1-hour average) and compares each value against the corresponding model threshold value. Whenever a receptor average exceeds the specified threshold, CONDEC examines each forecast period contributing to that average and determines the operating conditions that will meet all model threshold constraints.

Figure 1-3 is a graph of the threshold curve. The 3-hour and 24-hour SO_2 standards are shown on this graph to illustrate the "safety factor" between the threshold and the standards. The 3-hour and 24-hour threshold values on the curve are approximately 80% of the corresponding SO_2 standards. If SO_2 concentrations computed by the model for any receptor point exceed these model threshold values, control action is recommended in the computer output. The SCS forecasters analyze this output and then transmit to Kincaid twice daily a final recommendation for plant operations. Other features of both the AQFOR and CONDEC models are detailed in Appendix A.

The models used in this study had not yet been upgraded from their original design to include the experience gained in actual operations. It would naturally be expected that improvements could substantially increase the operational accuracy of the entire SCS.



Time Period (hours)	Threshold Values (ppm)
1-3	0.385
4-6	0.319
7-9	0.252
10-12	0.200
13-15	0.172
16-18	0.144
19-21	0.130
22-24	0.119

Figure 1-3 Model SO_2 Threshold Curve and Corresponding Threshold Values

2. SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

The reliability analysis technique developed in "Technique for Supplementary Control System Reliability Analysis and Upgrading" (EPA 1976a) has been tested in a case study using the Kincaid Generating Station SCS as an example. The reliability of the SCS has been tested in two ways: (1) the hour-by-hour ability of the SCS to predict the then-measured ground-level concentration has been evaluated by an error ratio technique and (2) the ability of the SCS to avoid exceeding NAAQS has been evaluated by a statistical combination of frequency distributions (accomplished by the computer program PROBL).

The error ratio analysis involved comparisons of real-time, maximum predicted ground-level concentrations to maximum measured concentrations occurring over the 123-day test period. Because the entire set of 1-hour average concentrations contains many hours with very small values, a threshold was established for use of the hour. In addition, subsets of the data were selected to overcome the lack of observed data at each model receptor point (256 points). The error ratio analysis is quite sensitive to the selection rules used to define these data subsets. Specifically, the statistics are systematically biased by the data selection criteria and by the value of the threshold concentrations. A further analysis of the source of errors in the SCS divides the total error into component parts; errors in forecasting the observed meteorology, errors in projecting the power plant emissions, and errors in modeling ground-level concentrations.

The conclusions of the error analysis follow:

- The error ratio has a value range between zero and infinity. It is therefore very sensitive to low values of either the predicted or observed concentrations. One data subset was defined by eliminating all hours where the observed concentration was less than 0.05 ppm (~135 $\mu g/m^3$). Since predicted concentrations in the range of 0 to 0.05 ppm still remained in the data set, a systematic bias towards low prediction results occurs. A bias toward underprediction occurs because of this lack of symmetry in the observed to predicted data base. The result is also a large variation in R_T. Two specific difficulties of the Kincaid SCS were found to account for much of the underprediction: 1) measured ground-level concentrations caused by other nearby SO_2 sources and 2) hours when the mixing depth was forecast to be lower than actually occurred, and the SCS predicted no contribution from Kincaid.

- When the same threshold is used for both the predicted and observed values the error analysis indicates that the SCS tends to overpredict and the scatter is greatly reduced. The symmetry between observed and predicted data sets is restored.
- When the predicted values are also restricted to monitored locations (instead of the entire field of receptors) the results do not change appreciably. One interpretation of this result is that data from the monitoring system around Kincaid is representative of the values resulting from the analysis of the entire receptor field.
- For the limited number of hours in which the predicted and the observed concentrations at a specific monitor were both above the threshold, the mean error ratio shows only a slight underprediction in the mean. This subset may be a good test of a model but represents a narrow test of the SCS. This is because the actual location of the predicted maximum is not the basis for a control action.
- If the subset is determined only by predicted concentrations above the threshold while measured concentrations can be any value, an exaggerated overprediction occurs, again because of the lack of symmetry in the data set.
- When the threshold is raised, the mean R_T and its standard deviation both decrease.

- The analysis was expanded to 3-hour and 24-hour average concentrations to determine if a larger safety margin existed with respect to the standards than is apparent from the 1-hour averaging time analysis. The 3-hour average results did not show any improvement. For the 24-hour averaging time, the mean safety margin was much higher, showing a tendency to overpredict the 24-hour average concentration.

- Separating the total system error R_T into its components was useful in suggesting that the "observed" meteorology did not result in model predictions as accurate as those using the predicted meteorology. This somewhat surprising finding suggests that short term predictions based on synoptic scale meteorological forecasts may have a higher reliability than meteorological inputs derived from on site measurements by instruments at heights that are low in relation to plume heights.

- The error ratio analysis techniques provide a method for generating gross statistics concerning the SCS model reliability. Two cautionary notes are appropriate for future applications of this technique.

    1) The breakdown of the total system error into component error ratios provides insight. The analysis for Kincaid showed that very reasonable total system error ratios resulted from the balancing of overprediction and underprediction factors of the error ratio components.

    2) Because the error ratios are severely affected by extremely low values of measured or predicted values, care must be taken to ensure that the results are applicable to the highest air quality concentrations which by their very nature focus on the occurrences of worst-case meteorological conditions. For this reason thresholds should be used in the development of any meaningful statistics for SCS reliability. Separate consideration should also be given to evaluating SCS reliability from a worst-case analysis point of view.

The analysis for Kincaid using the error ratio method has revealed some important characteristics about that method.

The analysis of each hour of a test period and the consequent averaging of all the results is less useful than the analysis of only those hours with significant measurements. To retain symmetry in the data base, thresholds need to be applied also to the predicted values. It is difficult to establish a criterion by which to judge an SCS's performance. An ideal R_T of 1 with a small geometric standard deviation (the minimum is 1) appears to be difficult to attain. If a sector-averaged model is used, as is appropriate to protect against exceeding the standards, it was shown that large means and standard deviations could be expected.

The second portion of the reliability analysis is the application of the PROBL program to the frequency distributions of emissions, meteorology and SCS total error ratio R_T to evaluate the expected percentage of the time when the standards might be exceeded despite the SCS efforts. This analysis, based on the data subset with the worst SCS predictive result, projects that the concentrations due to emissions from the Kincaid Station are expected to exceed the 3-hour standard less than once per period. The test period was 123 days and the percentages may not be valid for any other time period, but they are indicative of the general situation. Because R_T values are higher for 24 hours, the expectation of exceeding the 24-hour standard (although untested in this study) would be even lower.

The following conclusion can be drawn. The reliability analysis technique, error ratios plus PROBL, developed previously and tested in this study provides a method of analyzing the large quantity of SCS data to assess the overall reliability of an SCS. The data base for developing the inputs to PROBL did not include enough observed concentrations near the NAAQS to define clearly the frequency distributions used at the high concentration end. Nevertheless, the result of the PROBL analysis indicates expected violations less than once per year, indicating that the Kincaid SCS is reliable. This result occurs despite the use of the original model that had not yet been upgraded based on operational experience.

It has become clear, however, that the analysis techniques do not provide a logical method for the upgrading of SCS forecasting techniques. It is believed that what is true at Kincaid is true elsewhere; in other words, that observed meteorology is the greatest weakness in verifying model results. It is also clear that investigating the individual hours (such as Case 4), when the forecast system most radically underpredicted the observed concentrations, is far more likely to result in model and forecast methodology improvements than the use of the techniques described and used here. This suggests only limited continued use of these techniques and more effort to be placed on modeling and forecasting the worst-case situations.

3. RELIABILITY ANALYSIS METHODS

3.1 Discussion of Error Ratios

A complete SCS has four general components in which uncertainties can exist. These components are (1) air quality monitoring, (2) meteorological forecasting, (3) emissions forecasting and (4) air quality modeling. The first of these, air quality monitoring, differs significantly from the other three components in that inaccuracies in monitoring, if they go undetected, cannot be quantified. Inaccuracies in measured concentrations can be divided into two categories: instrumenation errors that result in inaccurate measurements of ground-level concentration, and failure to monitor the maximum ground-level concentration because of inappropriate or insufficient deployment of monitors. In either event, the actual maximum ground-level concentration will not be accurately measured.

The first of the possible monitoring errors, instrumentation inaccuracies, has received a great deal of attention. Significant portions of the formal structure of an operating monitoring system, especially a real-time system for an SCS program, are devoted to monitoring accuracy. A complete field testing and calibration system provides measurement accuracies traceable to the National Bureau of Standards. In addition, it is common to invest significant time and energy in editing and validating the monitored data once received. Such a quality assurance program is the only means to assess the reliability of the measured concentrations. Any system will, of course, have missing data. The more data the system captures, the less likely that maximum ground-level concentrations will be missed.

The second reliability factor in measured concentrations, the number and placement of monitoring stations, has been addressed in detail in ERT's previous report on reliability analysis (ERT 1974). Using an air quality model and an example source emission, it was shown that in order to observe more than 90% of all SO_2 concentration values greater than 0.25 ppm, it would be necessary to have 25 monitoring stations located around the source. If the threshold concentration were reduced to 0.1 ppm, the 25 monitors would observe only 72% of the maximum concentrations. It should be noted that adding the 25th station increased the percentage of observed maxima by only 0.3% for the 0.25 ppm threshold. Because of the expense of a monitoring station, it is clear that all reasonable sets of monitoring stations will miss a relatively high percentage of significant peak values. Hence, if violations are expected to occur and monitoring alone is used to guide the decisions to control emissions, a significant number of undetected violations will occur. For this reason, and also because many sources require advanced warning of the need for emission reduction, for an SCS program to be reliable it must forecast expected severe meteorological conditions and/or predict expected ground-level concentrations.

The other three components of an SCS program in which uncertainty can exist, meteorological forecasting, emissions forecasting and air quality modeling, are interrelated and are portions of the mechanism for predicting ground-level concentrations. The error in an SCS system at any given time can be characterized by the ratio between the maximum predicted concentration and the maximum observed concentration. In equation form, that is:

$$R_T = \frac{C_p}{C_o}$$

where

R_T is the total error ratio of the SCS system,

C_p is the maximum predicted concentration and

C_o is the maximum observed concentration.

The definition of C_p can be expanded to show its dependence on Q_p, the expected emissions from the source and, in a more complex way, upon M_p, a variable that includes the meteorological parameters which affect plume dispersion. The equation for R_T therefore becomes:

$$R_T = \frac{C_p(Q_p, M_p)}{C_o}$$

Hence, if the complete air quality forecast C_p (Q_p, M_p) were correct, it would equal C_o, and the ratio R_T would equal 1. Although it is not possible to deduce errors in C_o using the above equation, errors in C_p can be deduced by comparison to a "validated" C_o.

Three possible sources of uncertainty are mentioned above. They can be included specifically in R_T through the following equation:

$$R_T = R_w \cdot R_q \cdot R_m$$

where

R_w is the error ratio for meteorological (weather) forecasting,

R_q is the error ratio for emissions prediction and

R_m is the error ratio for air quality modeling.

By separating the total SCS error R_T into three components that can be addressed individually, the relative magnitude of each component can be assessed. As experience with an SCS program is gained, isolation of the factors responsible for total system error R_T provides a reasonable mechanism for determining areas for improvement.

Since R_T is defined as a ratio of concentrations, it is desirable to have each of its component ratios also defined in terms of concentrations. The only effective way to produce concentrations for comparisons in the ratios is through an air quality dispersion model. Of course, it is desirable to use the same model for development of each ratio leading to the total system error. Because the model, therefore, becomes an important part of the analysis technique, R_m, the air quality modeling error, shall be defined first.

The error in the model is defined by the ratio of the concentrations calculated with the model using observed meteorology and observed emissions to the measured ground-level concentrations. This ratio can be represented by the equation:

$$R_m = \frac{C_p(Q_o, M_o)}{C_o}$$

in which $C_p\ (Q_o,\ M_o)$ is the maximum predicted concentration with observed emissions and observed meteorology. The model used for evaluating ground-level concentrations must be used consistently in this and the subsequent ratios.

The error due to the effect of incorrectly forecasting emissions, R_q, is the ratio between the ground-level concentration impacts calculated with predicted emissions and observed emissions. The equation is

$$R_q = \frac{C_p(Q_p,\ M_o)}{C_p(Q_o,\ M_o)}$$

in which $C_p\ (Q_p,\ M_o)$ is the maximum predicted concentration with forecast emissions and observed meteorology and $C_p\ (Q_o,\ M_o)$ is the maximum predicted concentration with observed emissions and observed meteorology. Note that the ratio compares model evaluations of the ground-level concentration, keeping the meteorology constant. The ratio of the concentrations may or may not be simply the ratio of the emissions; for example, when a different sulfur content fuel is used for the same operating load at the plant (a fuel-switching SCS program), R_q would be equal to the ratio of emissions only (Q_p/Q_o). However, in a load-switching SCS program such as that at Kincaid, or when the load of the power plant varies, the change in load affects not only the pollutant emissions, but also the plume rise. A decrease in load reduces the plume rise and brings the plume closer to ground-level, a change in the opposite direction as the reduction in total SO_2 emissions. R_q, therefore, must be defined as the ratio of concentrations that includes the effect of this change of plume rise.

The third and final error ratio is that ratio associated with meteorological forecasting, R_w. By a similar technique to that used for R_q, the ratio for meteorological forecasting error is the concentrations predicted by the model with forecasted meteorology divided by the concentration predicted with observed meteorology, or

$$R_w = \frac{C_p(Q_p,\ M_p)}{C_p(Q_p,\ M_o)}$$

in which $C_p(Q_p, M_p)$ is the concentration predicted by the model using predicted emissions and predicted meteorology, and $C_p(Q_p, M_o)$ is the concentration predicted by the model using predicted emissions and observed meteorology. This formula, therefore, represents the ratio of predicted air quality concentrations using predicted versus observed meteorology, holding the emissions constant at the predicted value. This ratio defines the meteorological forecasting error in a very specific way, which is related not to the forecasters' ability to define the overall synoptic or dispersion situation, but to the forecasters' ability to specify model input parameters that yield accurate concentrations predictions.

It is appropriate here to discuss the meteorological input parameters. Most models require at least three basic meteorological inputs: wind speed, wind direction and stability class. The first two are usually derived at stack top height from available measurements at other heights. The third is normally derived empirically from some other measure of atmospheric stability. The temperature difference (ΔT) between two heights on a meteorological tower is often used to define atmospheric stability class. A fourth parameter that is often used is commonly termed the mixing depth. Mixing depth is the total vertical depth of the atmosphere through which it is assumed that the plume may be mixed. Normally, the plume can disperse upward without bound, but often meteorological conditions trap the plume below some specific height. Hourly mixing depth is approximated from National Weather Service radiosonde data, which is gathered twice a day, by interpolating to hourly values by using hourly surface temperature measurements. The forecaster, therefore, needs to assess each one of those four meteorological parameters accurately in order to strive for a value of R_w of 1.

It is now possible to give a more complete formula for the total system error ratio:

$$R_T = \frac{C_p(Q_p, M_p)}{C_p(Q_p, M_o)} \times \frac{C_p(Q_p, M_o)}{C_p(Q_o, M_o)} \times \frac{C_p(Q_o, M_o)}{C_o} = \frac{C_p(Q_p, M_p)}{C_o}$$

The separation of R_T into its component parts has not altered the fact that it is a ratio of the concentrations predicted with predicted emissions and predicted meteorology to measured concentrations. If each individual component were forecast precisely, then each of the component R's would equal 1, and the total R would equal 1. The two intermediate model predicted concentrations cancel, which means that errors in observed emissions and observed meteorology do not show up in the final error ratio R_T. However, errors in observed emissions or meteorology can be very important to the component R values. "Errors" in observed meteorology and observed emissions arise from inaccuracy and inappropriateness of measurements. For instance, if wind speed and wind direction at the top of a tower are unrepresentative of the plume path, an "error" in observed meteorology is the result. Errors may balance each other, however. If, for instance, R_q were 1, an error in observed meteorology that in the model resulted in a lower than measured concentration would create a low R_m, but might be offset by a high R_w so as to produce an $R_T \approx 1$. Another point worth noting is that the above formula could equally well have used predicted ground-level concentrations with observed emissions and predicted meteorology, $C_p(Q_o, M_p)$. Since changes in load affect the plume rise, observed meteorology rather than predicted meteorology was chosen for the plume rise calculation. R_q is therefore evaluated with observed meteorology.

An example may help to illustrate the approach. Table 3-1 gives an example of the error ratio method. Note that each of the component R values represents a slight overprediction and the total is therefore well over the measured value, C_o.

The method described above defines a quantitive way to calculate the total system error in an SCS program and the three major components of that error. This systematic approach provides a framework for analyzing the errors and therefore the reliability of an SCS program.

Because the total system error does not measure the ability of the SCS program to maintain the ambient air quality standards, a method for that analysis is given in Section 5.

TABLE 3-1

EXAMPLE OF ERROR RATIO METHOD

	Predicted	Observed
Meteorology		
Wind Direction (°)	150	148
Wind Speed (mps)	5	6
Mixing Depth (m)	800	500
Stability Class	4	4
Emissions		
Unit 1	0	0
Unit 2	530	500

Concentrations (ppm of SO_2)

$C_p(Q_p, M_p)$	0.084
$C_p(Q_p, M_o)$	0.080
$C_p(Q_o, M_o)$	0.076
C_o	0.060

$$R_T = R_w \times R_q \times R_m$$

$$R_T = \frac{C_p(Q_p,M_p)}{C_p(Q_p,M_o)} \times \frac{C_p(Q_p,M_o)}{C_p(Q_o,M_o)} \times \frac{C_p(Q_o,M_o)}{C_o} = \frac{C_p(Q_p,M_p)}{C_o}$$

$$R_T = \frac{0.084}{0.080} \quad \frac{0.080}{0.076} \quad \frac{0.076}{0.060} = \frac{0.084}{0.060} = 1.40$$

$R_w = 1.05$ $R_q = 1.05$ $R_m = 1.27$

3.2 Establishment of Cases for Analysis

As indicated in the previous section, it is unreasonable to maintain a monitoring system large enough to measure all maximum concentrations. While it is customary to analyze worst-case meteorology and the historical records at a specific site in order to locate the limited number of monitors for maximum coverage, this process still cannot cover all high concentration situations. As a result, an SCS program which employs an air quality model should make predictions for locations where no measurement is available. Because the number of points at which concentrations are predicted is larger than the number of points at which concentrations are observed in the limited monitoring network, a value of R_T greater than 1 on average should be expected.

In evaluating an entire 120 day test period of SCS program operation, it is evident that a large number of the individual hours may not be of much interest or import. For instance, for most nighttime hours, the plume remains well aloft and will not affect any of the monitoring stations in the flat terrain surrounding Kincaid. While the model will calculate relatively small concentrations at ground level, any differences could make substantial changes to the value of R_T . For this reason, it is appropriate in the analysis to use a threshold concentration value to limit the number of hours studied to those that are most important. Establishing a threshold for either the observed or predicted values produces, however, another systematic bias in the R_T values. Consider, for example, the data subset that is characterized by lower-than-threshold observations but includes the full range of predicted values. If this data subset is eliminated from the full data set, a systematic bias toward underprediction ($R_T < 1$) will result because the mean values of the observed data become higher when the values below the threshold are removed, while the mean value of the predicted set is not necessarily affected.

A number of cases have been constructed that attempt to define the biases caused by the lack of complete monitoring coverage and the use of threshold concentrations. These seven cases are presented in Table 3-2.

TABLE 3-2

SCS RELIABILITY ANALYSIS CASES

Case	Maximum Concentration Measured at a Monitor	Maximum Concentration Predicted in Real-Time
1.	Any Monitor > Threshold	Any Receptor
2.	Any Monitor > Threshold	Any Receptor > Threshold
3.	Any Monitor > Threshold	Any Monitor > Threshold
4.	Any Monitor > Threshold	Same Monitor > Threshold

	Maximum Concentration Predicted in Real-Time	Maximum Concentration Measured at a Monitor
5.	Any Receptor > Threshold	Any Monitor
6.	Any Monitor > Threshold	Any Monitor
7.	Any Monitor > Threshold	Same Monitor

The cases are defined as a set of hours with similar relationships of maximum concentration measured at monitors, C_o, to the maximum concentration predicted in real-time, $C_p(Q_p, M_p)$. It is useful to describe these cases individually and to indicate the expected bias.

The first four cases were culled from the 123-day test period by searching for each hour during which a concentration measured at any monitor exceeded the threshold. When the values at more than one monitor exceed the threshold, the monitor with the highest concentration is selected.

- In Case 1, the maximum measured concentration above the threshold is compared to the maximum predicted concentration at any receptor location surrounding the source, without regard to threshold. The receptors are defined as all those locations for which the air quality model makes an evaluation. This case is a severe test because a concentration above the threshold must be predicted for each hour that such a concentration was measured. The exact location of the predicted concentration is not important, however. For R_T to equal one, the prediction must simply be equal to the monitored concentration.
- Case 2 requires the additional condition that the maximum predicted concentration must be above the threshold value. This case still does not require that the model accurately predict the location of the maximum concentration, only its magnitude. This case should be a less severe test of the system because it eliminates all those cases where very little ground-level concentration was predicted. Case 2 is a subset of Case 1.
- In Case 3, the predicted maximum concentrations considered are only those at monitored locations. The threshold value is retained, but the concentration may be predicted at any monitored location, i.e., not necessarily the location where the maximum concentration was measured. Case 3 is a subset of Case 2.
- Case 4 adds an additional constraint: the maximum predicted concentration at a monitor occurs at the same monitor that

experienced the maximum measured concentration. This case represents a severe test of predictive accuracy as it requires that the correct location of the measured concentration be predicted. It is not clear that this is required in an SCS since a control action is initiated no matter what receptor is predicted to have a high concentration. The use of a threshold, however, on both concentrations limits the number of hours considered to those with some reasonable predicted value. Case 4 is a subset of Case 3 and represents the smallest data set of Cases 1 through 4.

- Cases 5 through 7 depend primarily on the maximum predicted concentration. Case 5 is developed by searching the entire test period for all those hours in which the predicted maximum concentration exceeded the threshold at any location in the model receptor grid. The maximum predicted concentrations are then compared to the maximum observed concentrations in the monitoring system. This is specifically the case which would tend to produce high values of the ratio, R_T, because the predicted maximum concentration may be nowhere near a monitored location or because no elevated concentrations may in fact have occurred during the hour, whether observed or not.
- Case 6 requires that the maximum predicted concentration be at a monitor site. Although each hour in Case 6 is one of the hours in Case 5, the maximum predicted concentration will generally differ since it must be at a monitor instead of at a receptor. Just as in Case 3, Case 6 would apply to a SCS that considers monitored sites only.
- Case 7 applies the constraint that the maximum measured concentration must be at the same location as the maximum predicted concentration. This case, like Case 4, is a test of the ability of the prediction system to forecast the correct location as well as the correct magnitude of a concentration.

The two groups of cases tend to show completely different aspects of the SCS reliability. Cases 5 through 7 will, in general, be biased towards overprediction, first because monitors are not located at all the receptors, and second because maximum measured concentrations have not been restricted by a threshold. Cases 1 through 4, however, are biased towards underprediction of the forecast system because of the emphasis on maximum monitored concentrations. By looking at the results of these two groups of cases simultaneously, a better understanding of the SCS as a whole can be obtained.

3.3 Data Collection and Processing

The evaluation of error ratios requires the collection and processing of a large quantity of data. The necessary values are the measured SO_2 concentrations, C_o, at each of the 10 monitoring sites and the following calculated ground-level concentrations:

- $C_p(Q_p, M_p)$
- $C_p(Q_p, M_o)$
- $C_p(Q_o, M_o)$

as they were described in Section 3.1. For the model calculations, the following input parameters are needed:

- plant emissions
- wind speed
- wind direction
- atmospheric mixing depth
- differential temperature (as a measure of stability)

Both the observed values of these parameters and the predicted values at the time of the forecast are needed. In the operational system at Kincaid, a forecast is made twice a day, at 0700 and 1600 hours Central Standard Time. Each of the input parameters is forecast and the AQFOR model is run on the computer. The results of these model runs are logged as well as stored on magnetic tape. This log enabled the study team for this project to select the maximum predicted concentration over the whole field or at any specific monitor. The hour-by-hour values of predicted concentration for the most recent forecast in relation to each hour are used. This log therefore provides $C_p(Q_p, M_p)$. Since the remainder of the analysis does not require M_p, there is no need to handle two sets of meteorological variables.

The other two model calculations require observed meteorological data and one requires observed emission data. These observations are available in real-time to the forecasters on duty and are, in fact, used as historical data in the AQFOR model calculations (the concentrations from previous hours are used to assess the probability of exceeding the 24-hour standard during the hours for which the forecast is being made). Although this observed data is placed in computer storage during the real-time retrieval, it is not considered valid until the strip chart data and calibration/maintenance reports have been received from the field. A two-step process follows. The first step, editing, eliminates from the data base all obvious errors in the values stored in the computer. It also eliminates values that are indicated as problems by calibration/maintenance. The second independent process, validation, samples the strip chart data for agreement with the numbers in computer storage. This process takes 30 to 45 days, after which the observed parameters become available for use.

A computer system could model concentrations for each hour of the test period (in this case 2952 hours). In this study, establishing a lower threshold of 0.05 ppm reduced the quantity of hours considered to two sets: the set for Cases 1 through 4, consisting of 321 hours, and the set for Case 5 through 7, consisting of 905 hours. A total of 177 hours was common to both sets so that a total of 1049 distinct hours, or 35.7% of the total hours in the 123-day test period, was considered.

Although the techniques for analyzing the error ratios could have been computerized, it appeared that the most cost-effective approach for this data set would be the use of a manual tabular mode of calculation. This procedure has been carefully reviewed and cross-checked to ensure the quality of the results.

One significant problem encountered in the processing of the concentration data was the treatment of "background" SO_2 from other sources. AQFOR is set up to add a background concentration depending on wind direction, wind speed and stability class to the predicted concentrations from the Kincaid plume. A background lookup table, Table 3-3, was developed for Kincaid during July and August of 1976 when the plant was not operating but the monitoring system was. This lookup table is, of course, specific to those two summer months and may be of less value for the winter months of the 123-day test period. An alternative method of background assessment could be provided by averaging the concentration values at monitors determined to be upwind, that is, not within a 90° sector of the observed wind direction. It was decided, however, that the predicted concentrations that the forecaster receives from AQFOR are based on the lookup table and therefore so is $C_p(Q_p, M_p)$. The other model calculations for C_p therefore ought to use the same background for consistency.

TABLE 3-3

BACKGROUND CONCENTRATIONS, ppm SO_2
LOOKUP TABLE FOR KINCAID
(BASED ON JULY-AUGUST 1976 DATA)

		Unstable						Neutral						Stable					
Wind Direction	No.	1	2	3	4	5	6	1	2	3	4	5	6	1	2	3	4	5	6
N	1	0.030	0.010	0.009	0.012	0.012	0.012	0.004	0.006	0.006	0.006	0.006	0.006	0.004	0.007	0.010	0.006	0.006	0.006
NNE	2	0.006	0.013	0.004	0.004	0.006	0.006	0.009	0.008	0.003	0.002	0.005	0.005	0.003	0.003	0.002	0.003	0.003	0.003
NE	3	0.007	0.011	0.005	0.007	0.007	0.007	0.008	0.004	0.004	0.005	0.005	0.005	0.004	0.003	0.003	0.004	0.004	0.004
ENE	4	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.008	0.008	0.008	0.008	0.008	0.004	0.005	0.005	0.005	0.005	0.005
E	5	0.008	0.008	0.008	0.008	0.008	0.008	0.015	0.009	0.010	0.010	0.010	0.010	0.004	0.005	0.004	0.006	0.004	0.004
ESE	6	0.004	0.004	0.004	0.004	0.004	0.004	0.006	0.008	0.010	0.007	0.007	0.007	0.005	0.006	0.005	0.005	0.005	0.005
SE	7	0.008	0.007	0.008	0.008	0.008	0.008	0.009	0.014	0.013	0.013	0.013	0.013	0.006	0.004	0.005	0.005	0.005	0.005
SSE	8	0.009	0.003	0.019	0.009	0.009	0.009	0.023	0.012	0.003	0.011	0.011	0.011	0.006	0.004	0.003	0.004	0.004	0.004
S	9	0.013	0.010	0.015	0.011	0.013	0.013	0.021	0.013	0.008	0.027	0.015	0.015	0.006	0.006	0.008	0.006	0.006	0.006
SSW	10	0.012	0.016	0.010	0.013	0.013	0.013	0.020	0.016	0.023	0.020	0.020	0.020	0.005	0.009	0.011	0.008	0.008	0.008
SW	11	0.010	0.012	0.009	0.011	0.010	0.010	0.002	0.013	0.011	0.004	0.010	0.010	0.004	0.004	0.009	0.004	0.004	0.004
WSW	12	0.020	0.003	0.002	0.002	0.003	0.003	0.004	0.003	0.004	0.004	0.004	0.004	0.002	0.002	0.002	0.002	0.002	0.002
W	13	0.003	0.003	0.003	0.003	0.003	0.003	0.010	0.003	0.003	0.005	0.005	0.005	0.004	0.003	0.003	0.003	0.003	0.003
WNW	14	0.012	0.012	0.012	0.012	0.012	0.012	0.008	0.008	0.008	0.008	0.008	0.008	0.002	0.006	0.003	0.003	0.003	0.003
NW	15	0.009	0.011	0.004	0.009	0.009	0.009	0.020	0.014	0.007	0.014	0.014	0.014	0.003	0.002	0.013	0.004	0.004	0.004
NNW	16	0.009	0.009	0.007	0.009	0.009	0.009	0.005	0.014	0.006	0.009	0.009	0.009	0.005	0.004	0.008	0.005	0.005	0.005

Columns labeled 1-6 represent different wind speed classes.

Class	Wind Speed Range (mph)
1	0-4
2	5-8
3	9-12
4	13-16
5	17-20
6	21-greater

4. RESULTS OF RELIABILITY ANALYSIS

4.1 Total System Error R_T

Table 4-1 presents a summary of the R_T analysis results. The geometric mean and standard deviation have been used to characterize the distribution of R_T values. The R_T values are bounded by 0 and infinity (if a zero observed value occurs) with an ideal mean value of 1. Because of these bounds, geometric statistics appear more appropriate than arithmetic statistics (see Figure 4-1).

The geometric mean has been calculated by:

$$\overline{R}_T = (R_1)(R_2)\ldots.(R_n)^{\frac{1}{n}}$$

where n is the number of hours in the case.

The geometric standard deviation has been determined by:

$$S = \exp\left[\frac{\Sigma(\ln R_i)^2 - \frac{(\Sigma \ln R_i)^2}{n}}{n-1}\right]^{1/2}$$

where R_i is the value of R_T for the ith hour. Note that in contrast to the arithmetic standard deviation, for which zero denotes no variations from the mean value, the minimum value of S (corresponding to no variations from the mean value of R_T) is unity. Therefore, the ideal value of S is 1.0.

If distributions of R_T are log normal, 68.3% of the values are contained between the values $\overline{R}_T/S$ and $(\overline{R}_T)(S)$. Using Case 1 as an example, where the arithmetic mean and standard deviation are 0.86 and 0.90, respectively, 68.3% of the values lie between R = 0.09 and R = 1.80.

Before reviewing the specific results of the case analyses, it is of interest to obtain a better feeling for the expected values of the mean value, R_T, and variations about this mean as evaluated with S.

TABLE 4-1

SUMMARY OF RESULTS FOR R_T

Case	Number of Hours	Geometric Mean R_T ($\bar{R}_T$)	Geometric Standard Deviation (S)	Complete Range of R_T Values	$\bar{R}_T/S$	$(\bar{R}_T)(S)$
1	321	0.40	4.49	0.02 - 6.69	0.09	1.80
2	177	1.22	1.77	0.26 - 6.69	0.69	2.16
3	66	1.21	1.79	0.31 - 6.56	0.68	2.17
4	22	0.86	1.72	0.38 - 3.50	0.50	1.48
5	905	4.37	2.72	0.14 - 44.00	1.61	11.89
6	288	3.56	2.65	0.38 - 29.67	1.34	9.43
7	58	2.33	2.76	0.38 - 22.33	0.84	6.43

See Table 3-2 for definition of cases. The threshold used is 0.05 ppm.

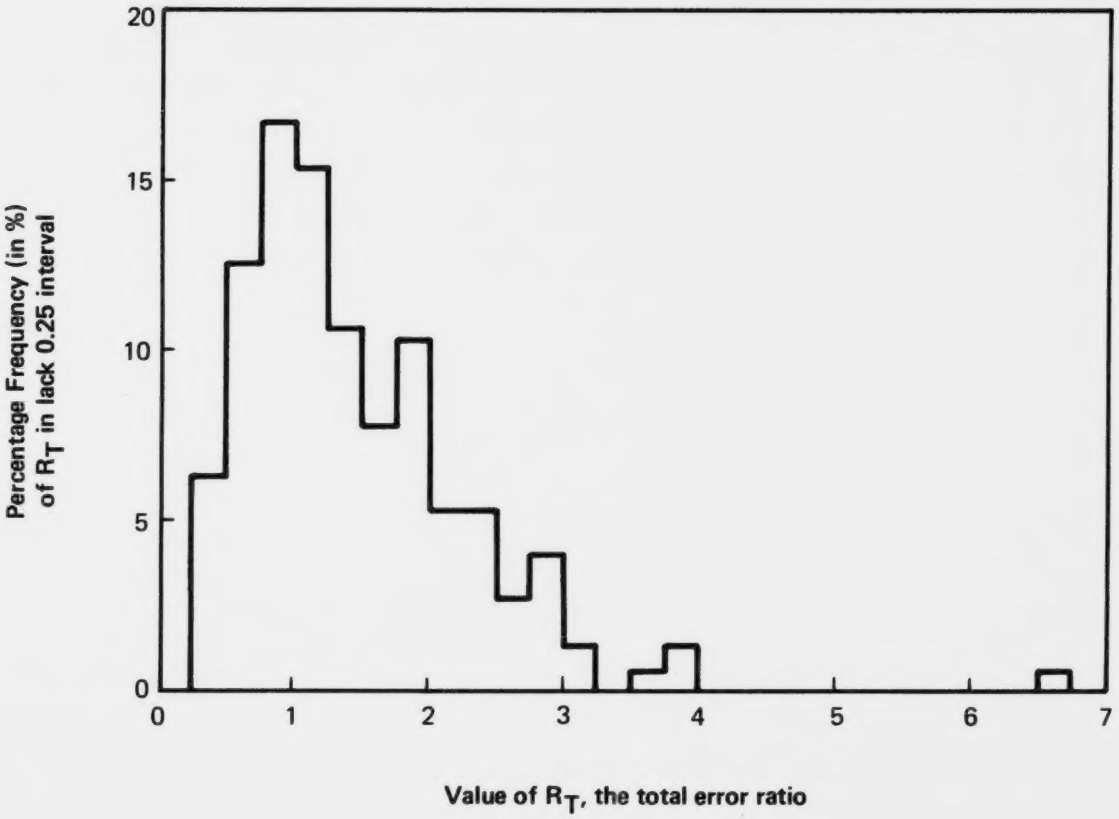


Figure 4-1 Histogram of R_T versus Percentage Frequency for Case 2 (177 hours of data)

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Consider the uncertainty associated with not knowing one meteorological variable wind direction exactly. We have estimated the 1-hour averages as if concentrations were uniformly distributed over a 22-1/2° wind direction sector. This is, in effect, a concentration value that better represents the average of a large number of measurements. Now suppose that, for any given hour, the actual concentration distribution was Gaussian and centered about a specific wind direction, within the 22-1/2 sector. Depending on the actual wind direction, a monitor located on the centerline of the sector would be expected to measure concentrations that could be above or below the sector-averaged values. However, by our definitions, the arithmetic average would equal the sector-averaged value. What values of R_T and S could be expected from the effect of this uncertainty in wind direction alone?

The ratio of the predicted (sector averaged) to observed (Gaussian) for any single event of this idealized situation would be given by:

$$R_T = \frac{\dfrac{2.03}{\sigma_z x}}{\dfrac{1}{\pi\sigma_y\sigma_z} e^{-y^2/2\sigma_y^2}} = \frac{2.03\pi\sigma_y}{x} e^{y^2/2\sigma_y^2}$$

where

x = distance to receptor from source

σ_y, σ_z = diffusion coefficients at distance x for a specific atmospheric stability category

y = crosswind distance from plume centerline

$$\bar{R}_T = \exp\left[\frac{1}{y_{max}} \int_o^{y_{max}} \ell n \left(\frac{2.03\pi\sigma_y}{x} e^{y^2/2\sigma_y^2}\right) dy\right]$$

where

y_{max} = distance from plume centerline to edge of 22.5 sector, i.e., x tan 11.25°

The integration in the above formula yields:

$$\bar{R}_T = T \, e^{y_{max}^2/6\sigma_y^2}$$

where

$$T = \frac{2.03\pi\sigma_y}{x}$$

Similarly, the geometric standard deviation can be derived as

$$S = \exp\left(.149 \frac{y^2}{\sigma_y^2}\right)$$

Now we can make an evaluation, but the distance x and the stability category must be specified. With the ASME unstable category at 2,000 meters from the source, $\bar{R}_T = 1.21$ and $S = 1.47$. The plume fits well in the sector for those conditions (value at y_{max} only 0.349 of the sector average) and the $\bar{R}_T$ and S values are small. At ASME neutral category and 6,400 meters from the source, the plume is quite narrow with respect to the sector (value at y_{max} is 0.000366 of the sector average) and $\bar{R}_T = 6.22$, while $S = 15.18$. This exercise demonstrates that even in idealized situations the use of R_T and S as measures of system error and/or reliability can be misleading. Moderately large values of S can be associated with a system which is in fact very reliable. Also note that the allocation of continuous variables such as wind speed and atmospheric stability into discrete categories in many modeling approaches results in errors that affect $\bar{R}_T$ and S (primarily) by producing an irreducible limit to the expected accuracy of predictions. No attempt is made in this study to quantify this lower accuracy limit for the Kincaid system.

The results in Table 4-1 cover the entire 123-day test period. The results were evaluated one month at a time, but a review showed no significant month-to-month variations except those caused in some months by very small sample sizes. Month-by-month summaries are therefore not presented.

A discussion of the results for R on a case-by-case basis follows. It is helpful to refer to the definitions of the seven cases found in Table 3-2. The threshold value selected is 0.05 ppm.

4.1.1 Case 1

Case 1 contains 321 hours in which the maximum monitored concentration was greater than 0.05 ppm. As can be seen from the geometric mean of 0.40, the values are in general underpredicted and the ratios have a fairly large geometric standard deviation. Underprediction is expected from the bias of the sample in Case 1, caused by the inclusion of predicted values below the threshold. There are bound to be many times when the SCS would not forecast ground-level concentrations above background at any receptor, while the monitors could measure a concentration above the threshold. Such a situation might occur when stable atmospheric conditions are predicted, which then lead to very small concentration predictions since the plume is modeled to remain elevated. If the stable conditions actually occur, then the monitored ground-level concentrations may be due to other nearby low-level sources of SO_2. The SCS would be using only the average background concentrations from the lookup table and thus would underestimate the measured concentration while not underestimating the impact of the Kincaid plume. This situation has undoubtedly occurred.

Another source of the low ratios is the set of events for which the measured concentrations are just above the threshold, while the predicted concentrations are small or equivalent to background. In order to quantify how sensitive the results are to the threshold value, the hours for Case 1 were reviewed for thresholds of 0.10 ppm and 0.14 ppm. The comparative results are presented in Table 4-2. These results demonstrate the sensitivity of the results to threshold. The higher the threshold, the lower the geometric mean and therefore the greater the underprediction. In the extreme case of the 0.14 threshold, the entire first standard deviation is below an R of 1. Note, however, that this is a small sample size representing only the highest 28 hours of measured concentrations.

TABLE 4-2

SUMMARY OF RESULTS FOR R_T
COMPARISON OF THRESHOLDS

Threshold ppm	Number of Hours	Geometric Mean ($\bar{R}_T$)	Geometric Standard Deviation (S)	Complete Range of R_T Values	$\bar{R}_T/S$	$(\bar{R}_T)(S)$
			CASE 1			
0.05	321	0.40	4.49	0.02 - 6.69	0.09	1.80
0.10	76	0.28	3.67	0.02 - 2.22	0.08	1.03
0.14	28	0.25	3.03	0.02 - 1.09	0.08	0.76
			CASE 2			
0.05	177	1.22	1.77	0.26 - 6.69	0.69	2.16
0.10	21	1.09	1.34	0.59 - 2.22	0.81	1.47

Another reason for the underpredictions evident in Case 1 is the use in this study of a sector-averaged model in the prediction of 1-hour averaged concentrations for comparison to measured data. A sector-averaged model is used in AQFOR because the SCS is oriented toward protecting against exceeding the 3-hour and 24-hour standards. To realistically assess the average for multiple hours, average expected 1-hour values rather than peak 1-hour values are used in the calculations.

4.1.2 Case 2

The Case 2 hours are a subset of the Case 1 hours with the additional restriction that a concentration must have been predicted above the threshold of 0.05 ppm at some receptor. Both predicted and observed values are above the threshold, and the bias identified in Case 1 is eliminated. The sample size, however, was reduced from 321 to 177 hours.

Case 2 does show considerably better statistics. On the whole, when the SCS is predicting a significant concentration, that prediction is within a factor of two a high percentage of the time. The mean value of R_T is greater than 1.0.

If the threshold in Case 2 is raised from 0.05 ppm to 0.10 ppm, the result is a very good geometric mean ratio and standard deviation as shown in Table 4-2. There are many hours for which neither the model nor the monitors produced any significant ground-level concentration. When these hours are eliminated from consideration, the model produces a more accurate description of the expected concentration.

4.1.3 Case 3

Case 3 adds the additional restriction that the receptor for which the SCS made a prediction must be a monitor site. This case shows very little statistical difference from Case 2 even through 111 hours have been dropped. This fact implies that the monitoring field provides a good sample of the entire receptor field since the results for the data subset for monitored locations are nearly the same as the results for the subset for all receptors.

4.1.4 Case 4

In Case 4, both the measured and predicted values above the threshold must be at the same monitoring site location. Only 22 hours fit the criteria of the case, which shows that only rarely did the SCS predict the exact location where a concentration was subsequently measured. The percentage is, in fact, 6.9% of all hours with measured concentrations greater than 0.05 ppm. This fact appears to demonstrate that the SCS must make predictions for a large number of receptor points and provide for control actions on the basis of expected contravention of standards at any one of those points. An SCS should act on predicted concentrations regardless of the location estimated for the maximum impact.

Case 4 represents a test of the ability of the SCS to predict at a specified point the expected concentrations quantitatively. Since concentrations above the threshold are both measured and predicted at the same location, the comparison illustrates one measure of the validity of the SCS prediction. Case 2 is the other best test because in fact in an SCS one does not generally care where the highest values are predicted if the value is accurate. Case 4, however, has been used as an example in some of the subsequent analyses in this section.

The statistics for Case 4 are quite reasonable despite the limited sample size. The geometric mean of 0.86 shows a tendency for slight underprediction (recall the underprediction is, in fact, expected since sector-averaged predicted values are being compared to 1-hour averaged observations), but most of the values are within a reasonable range of the perfect score of 1. The lowest value for R is only 0.38.

4.1.5 Cases 5 through 7

Cases 5 through 7 are based on data selection rules in which the predicted values are above a threshold and thus have a strong bias toward overprediction. Significant concentrations (in excess of 0.05 ppm) were predicted for 905 hours or 30.7% of the hours in the 123-day test period. There were only 321 hours (10.9%) when significant concentrations were measured. These figures are reasonable since significant concentrations are often predicted at locations with no monitor. It appears, however, that there are also many circumstances in which the SCS overpredicts the concentrations that are measured at ground level. The statistics of Cases 5 through 7 support that judgment since even Case 7, which involves comparisons at the same monitor, shows a geometric mean greater than 2. Note that there is no threshold restriction on the measured value for any of these cases. Note also that applying a threshold restriction to the Case 7 data set would result in a case equivalent to Case 4.

4.1.6 Summary of Cases

The analysis of Cases 1 through 7 demonstrates the sensitivity of the predictive statistics to concentrations below the threshold. Bias towards overprediction occurs when the threshold is applied to predicted concentrations and not measured, while a bias toward underprediction occurs when the threshold is applied to observed and not predicted concentrations. When thresholds are applied to both observed and predicted values (Cases 2, 3 and 4), there is a slight overprediction, and the standard deviations are much smaller.

4.2 Analyzing Error Ratios of SCS Components

To understand more fully the complex processes that are summarized in Table 4-1, consider the results for the three components R_w, R_q and R_m. Table 4-3 presents the geometric means and standard deviations for the components. Multiplying the mean values of each of the components in a case gives, within round-off errors, the R_T value for that case.

Several general statements about the results in Table 4-3 can be made. The prediction of the emissions is very good and the impact of errors in emission projections on the total error is relatively insignificant. This effect is caused by two factors: (1) in a base-loaded plant, the load is normally not expected to vary greatly from hour to hour, and prediction of load should be and is fairly accurate (especially when one of the units isn't operating, which reduces generation resources, a situation that existed during much of the test period) and (2) differences in emission strength are somewhat offset by plume rise. The second effect arises because the method compares the effect of

TABLE 4-3

SUMMARY OF RESULTS OF R_w, R_q, R_m
THRESHOLD OF 0.05 ppm

Case	Number of Hours	R_w		R_q		R_m		$(\bar{R}_w)(\bar{R}_q)(\bar{R}_m)$
		$\bar{R}_w$	S	$\bar{R}_q$	S	$\bar{R}_m$	S	
1	321	1.19	4.51	1.00	1.32	0.34	4.83	0.40
2	177	1.90	4.79	1.04	1.38	0.61	4.66	1.21
3	66	5.69	4.50	1.01	1.06	0.20	4.74	1.15
4	22	3.92	3.69	1.02	1.08	0.21	3.57	0.84
5	905	3.29	5.56	1.00	1.47	1.34	5.34	4.41
6	288	7.03	4.09	0.99	1.27	0.50	4.31	3.48
7	58	5.63	4.01	1.01	1.15	0.41	3.83	2.33

predicted and observed emissions on ground-level concentrations. If load is higher at Kincaid, emissions are higher, but so is plume rise, which reduces ground-level concentrations. This observation does not imply that estimates of Q are always correct. In any specific hour, the error in emissions prediction may significantly affect the accuracy of the concentration prediction.

The statistics for model error, R_m, indicate that the model is largely at fault in failure to achieve a reasonable R_T. The results indicate that, except for Case 5, the model on the average underpredicts the measured concentrations. The standard deviations are uniformly large, indicating a wide variation in results. Thus, even when the observed meteorology is used, the concentrations predicted by the model apparently are not conservative.

The geometric mean of R_m is lower than that of R_T, which implies that some component of the SCS counteracts the modeling tendencies to underpredict. A quick review of the R_w shows that these values are generally higher than 1 and do provide the offset required to raise the overall R_T values above those provided by the model, which implies that the forecasted meteorology, when converted to ground-level concentrations, is much more conservative on the average than the observed meteorology. These effects on R_w and R_m suggest that the observed meteorology may be the parameter that causes the high value of R_w and the low value of R_m. To check this hypothesis, the study examined the individual values in Case 4. This case was chosen because it compares observed and predicted values at the same monitor location.

Table 4-4 summarizes the results of the detailed analysis of Case 4. Beside each small value of R_m is given a major reason for the underprediction of the observed concentration, C_o, by the model with observed meteorology. Hour 3 is an example of the difficulty often experienced with mixing depth. The meteorological forecast called for significant concentration at the monitor, and the mixing depth was forecast to be well above a height that would have any significant effect. In the observed meteorology, two radiosonde soundings at Peoria, Illinois, are interpolated to determine the mixing depth. This observed mixing depth for Hour 3, 450 meters, was so low that the model assumed that the plume entered and remained in the elevated stable

TABLE 4-4

DETAILS OF CASE 4

										Meteorology							
					Load (Mw)				Wind Direction (degrees)		Wind Speed (mph)		Mixing Depth (m)		Stability	
					Unit 1		Unit 2									
Sample Hours	C_o	R_T	R_w	R_m	Reason	OBS	PRED	OBS	PRED	OBS	PRED	OBS	PRED	OBS	PRED	OBS	PRED
1	0.162	0.59	1.09	0.52	4	0	0	530	550	338	340	11	13	3,000	500	3	4
2	0.136	0.63	0.99	0.63	4	0	0	529	550	346	340	11	14	3,000	500	3	4
3	0.055	1.09	7.5	0.15	1	0	0	532	550	176	175	9	12	450	3,000	4	4
4	0.158	0.44	0.77	0.41	4	0	0	368	550	219	230	18	12	500	3,000	1	4
5	0.079	0.72	19.0	0.04	2	0	0	185	250	281	290	13	8	3,000	900	1	4
6	0.060	1.33	1.05	1.27		0	0	529	530	180	180	21	17	500	800	4	4
7	0.053	1.74	30.7	0.06	2,4	0	0	534	535	273	290	12	12	3,000	500	1	4
8	0.067	0.84	2.95	0.28	2	250	300	0	0	163	180	11	8	500	600	2	4
9	0.062	0.87	2.84	0.31	2,4	270	300	0	0	164	185	12	9	500	3,000	1	4
10	0.072	0.76	2.89	0.26	2	291	400	0	0	164	185	11	9	600	3,000	2	4
11	0.062	0.89	3.67	0.24	2	361	400	0	0	174	190	12	9	700	3,000	3	4
12	0.054	1.63	6.29	0.26	2	169	100	539	550	316	300	22	18	3,000	3,000	4	4
13	0.087	0.82	23.7	0.03	2	0	0	532	550	272	290	7	16	3,000	3,000	2	4
14	0.125	0.57	23.7	0.02	2	0	0	522	550	267	290	7	16	3,000	3,000	2	4
15	0.127	0.52	0.86	0.57	1,4	0	0	510	550	221	230	21	15	500	3,000	1	4
16	0.179	0.38	5.23	0.07	1	0	0	484	485	176	190	20	20	200	3,000	3	4
17	0.077	0.86	0.83	1.01		0	0	476	485	183	190	29	22	300	3,000	1	4
18	0.129	0.52	3.35	0.16	2,3	557	550	539	550	204	190	2	7	3,000	3,000	4	4
19	0.126	0.53	3.19	0.17	3	567	550	507	550	181	190	3	7	3,000	3,000	4	4
20	0.068	2.01	0.60	3.40	2	557	535	529	535	151	170	14	14	400	3,000	4	4
21	0.074	3.53	23.5	0.15	2	553	530	550	530	148	155	15	12	600	400	4	4
22	0.052	0.98	17.0	0.06	2,4	0	0	529	550	262	340	7	8	3,000	700	5	4

Reasons Code

1. Observed mixing depth assumes plume is trapped in elevated layer.
2. Observed wind direction puts plume in different sector.
3. Observed wind speed caused plume rise to be too high.
4. Observed stability class caused alteration of the position of the maximum.

layer. Consequently, the model with the "observed" meteorology did not predict any plume impact, only the background lookup concentration. Hence, the forecast was "right" and the "observed" meteorology was wrong.

A more frequent difficulty in this example is that the observed meteorological wind direction places the plume outside the sector of the target monitor (the model predicts a sector-averaged value for the 22-1/2° sector centered about the observed wind direction). This suggests that the predicted wind direction, which is forecast from synoptic considerations, was more accurate for estimating plume trajectories than the observed wind direction at a height of 60 meters on the meteorological tower. The plume, which exits from the stacks at 152 meters and rises many meters more may be influenced more by the synoptic weather pattern than the wind direction at 60 meters. Therefore, the concentration predicted with the forecast wind direction derived from synoptic analysis may often be more realistic.

Another reason for differences between the predictions with observed and predicted meteorology is caused by inappropriate observed stability class. Differential temperature measurements at the meteorological tower were discovered to overestimate the instability of the atmosphere. Therefore, the concentration profile given by the model with observed meteorology had maxima that occurred too close to the power plant and underprediction occurred at the monitor. The forecasters had suspected this situation for quite some time and were adjusting for it, as is evidenced by the column of predicted stability classes.

In order to test the potential errors in the differential temperature measurements, another source of stability class estimates was needed. The Springfield, Illinois, Airport is some 31 kilometers northwest of the Kincaid Station, and hourly observations were used to develop Turner stability classifications for the hours of Case 4. These classifications along with the other meteorological parameters at Springfield and Kincaid are presented in Table 4-5.

The Springfield-derived stability classifications support the judgment of the forecasters and imply that the "observed" stability class at Kincaid is for the most part incorrect. The observations of wind speed and wind direction that were made at Springfield generally

TABLE 4-5

COMPARISON OF METEOROLOGICAL DATA OBSERVED AT KINCAID AND AT SPRINGFIELD*

CASE 4

	Wind Direction*			Wind Speed (mph)			Springfield		Stability		
	Kincaid		Springfield	Kincaid		Springfield	Cloud Cover	Ceiling	Kincaid		Springfield
Hour	Obs.	Pred.	Obs.	Obs.	Pred.	Obs.	(tenths)	(100's ft)	Obs.[1]	Pred.	Obs.[2]
1	338	340	340	11	13	15	.2	250	3	4	4
2	346	340	10	11	14	16	.7	250	3	4	4
3	176	175	120	9	12	4	1.0	7	4	4	4
4	219	230	230	18	12	23	.7	200	1	4	4
5	281	290	270	13	8	16	.7	30	1	4	4
6	180	180	170	21	17	18	0	-	4	4	4
7	273	290	270	12	12	15	.8	100	1	4	4
8	163	180	170	11	8	12	.2	250	2	4	4
9	164	185	270	12	9	12	.1	250	1	4	4
10	164	185	160	11	9	10	.1	250	2	4	3
11	174	190	180	12	9	12	.1	250	3	4	4
12	316	300	330	22	18	18	0	-	4	4	4
13	272	290	280	7	16	9	.5	250	2	4	3
14	267	290	250	7	16	12	.4	250	2	4	4
15	221	230	240	21	15	22	.8	130	1	4	4
16	176	190	170	20	20	21	1.0	250	3	4	4
17	183	190	170	29	22	24	1.0	250	1	4	4
18	204	190	150	2	7	3	1.0	35	4	4	4
19	181	190	150	3	7	5	1.0	35	4	4	4
20	151	170	150	14	14	16	1.0	7	4	4	4
21	148	155	150	15	12	17	1.0	6	4	4	4
22	262	340	220	7	8	9	.8	12	5	4	4

[1] Generated from differential temperature measurements.

[2] Turner classification scheme.

*Observations made on the hour.

agree with the observations at Kincaid. Observations of wind characteristics at plume height would appear to be needed to verify the forecast values.

Using more accurate stability class determinations for the observed meteorology would better balance the R_m and R_w.

The information in Table 4-4 supports the hypothesis, which was derived solely from the error ratio analysis, that the observed meteorology was a source of difficulty. In fact, it appears that the predicted ground-level concentrations using forecast meteorology more accurately describe the observed concentrations than does the "observed" meteorology.

4.3 Background Concentrations

It is interesting to compare the background concentrations developed with monitored concentrations for July and August and used in the AQFOR model during the test period with those that were observed in the monitoring system around Kincaid. Since monitors are well placed around the source, it is always possible to select a monitor to represent the upwind concentrations. A quick resume of the situation is contained in Table 4-6, which presents a comparison for the Case 4 hours. Until December 24, there seems to be little real problem with the use of the lookup table background concentration. Errors in estimating background were only once greater than 10% of the observed maximum concentration. Data for December 24 and all of January indicate a much more difficult problem. Background SO_2 concentrations appear to be significantly higher, and in all of the examples the increase over the lookup table background is more than 10% of the observed maximum concentration. It seems logical that these higher background concentrations were associated with the severe cold experienced during the winter of 76-77 and with the increased fuel use.

Any background concentration different from the lookup value does, of course, affect the error ratio calculated for the SCS. The last column of Table 4-6 shows the R_T adjusted by the inclusion of the measured background concentrations instead of the lookup table values. Individual values of R_T have changed, and the geometric mean, $\overline{R}_T$, has risen slightly. The geometric standard deviation has not changed. The

TABLE 4-6

COMPARISON OF BACKGROUND CONCENTRATIONS LOOKUP TABLE VS. UPWIND MONITOR

		Background Concentration (ppm)				
Hour	Date	Predicted Lookup Table	Observed	Monitor	Maximum Monitored	Adjusted R_T
1	10/6	0.007	0.006	8	0.162	0.58
2	10/6	0.007	0.009	5	0.136	0.65
3	10/23	0.008	0.001	10	0.055	1.04
4	11/17	0.011	0.001	8	0.158	0.37
5	11/29	0.003	0.001	10	0.079	0.70
6	12/9	0.015	0.009	10	0.060	1.23
7	12/16	0.003	0.001	10	0.053	1.77
8	12/18	0.019	0.029	10	0.067	0.99
9	12/18	0.019	0.023	10	0.062	0.94
10	12/18	0.019	0.020	10	0.072	0.78
11	12/18	0.015	0.014	10	0.062	0.87
12	12/20	0.014	0.001	4	0.054	1.39
13	12/21	0.003	0.003	10	0.087	0.82
14	12/21	0.003	0.002	10	0.125	0.56
15	22/11	0.010	0.008	1	0.127	0.50
16	12/24	0.013	0.032	7	0.179	0.49
17	12/24	0.013	0.021	5	0.077	0.96
18	1/3	0.020	0.035	8	0.129	0.64
19	1/3	0.021	0.034	8	0.126	0.63
20	1/13	0.011	0.029	8	0.068	2.28
21	1/13	0.011	0.041	8	0.074	3.91
22	1/14	0.003	0.010	3	0.052	1.12
					$\bar{R}_T$	0.89
					S	1.72

effect of using actually measured background would only slightly improve system accuracy from this point of view. Real-time background data cannot be used for the forecast period, but would be of greater value than a lookup table. One possible improvement might be a seasonally-varying background lookup table.

The analysis of background concentrations revealed that some of the hours in Case 1 were for times when Kincaid was not operating. There were 18 hours when measured concentrations were above the 0.05 ppm threshold (range from 0.052-0.107 ppm) and were, therefore, included in the sample. The SCS only predicts the background lookup concentration. The geometric mean of those 18 hours was 0.07, and if they are removed from Case 1, the geometric mean, $\overline{R}_T$, is 0.45 and the geometric standard deviation, S, is 4.07 (compare to 0.40 and 4.49, respectively).

Clearly there were other sources contributing to monitored concentrations during those hours. For other hours, those sources also contribute. Several hours were found when winds from the northwest coincided with measured concentrations northwest of Kincaid that the SCS would not have forecast with the background lookup table based on summer data.

4.4 Three- and Twenty-Four-Hour Average Concentrations

All of the previous comparisons have used 1-hour averages. All input data as well as measured concentrations were averaged over one hour, and the model results interpreted to represent 1-hour values even though the model uses sector-averaged values that would normally only be applied for longer averaging times. The standards for SO_2 are, however, written as 3-hour averages (secondary standard) and 24-hour averages (primary standard). The data acquisition, storage and model processing required to do all the cases for the longer averaging times would be a significantly larger task than that for the 1-hour values. For this reason, a limited sample again was chosen to test the effect of longer averaging times. Case 4, again because of its observed versus predicted comparison at a single monitor, was selected. The results for 1-, 3- and 24-hour averaging times are presented in Table 4-7. Note that the number of samples decreases because the 3-hour and the 24-hour periods

TABLE 4-7

SUMMARY OF RESULTS FOR R_T AS A FUNCTION OF AVERAGING TIME

CASE 4

Averaging Time in Hours	Number of Samples	Geometric Mean $\bar{R}_T$	Geometric Standard Deviation (S)	$\frac{\bar{R}_T}{S}$	$(\bar{R}_T)(S)$
1	22	0.86	1.72	0.50	1.48
3	15	0.87	1.89	0.46	1.64
24	14	1.23	1.95	0.63	2.40

may contain more than one of the one-hour samples. The 3-hour comparisons are for the highest average 3-hour measured concentration while the 24-hour concentration were evaluated on a midnight to midnight basis. Two results are discernible: (1) the SCS does not predict 3-hour average concentrations any more reliably or accurately than 1-hour concentrations; and (2) the SCS does not predict 24-hour average concentrations any more accurately, but predicts 24-hour average concentrations somewhat more conservatively than 1-hour concentrations.

4.5 Prediction of Meteorological Parameters

The forecaster's primary function is to determine the values of meteorological forecast parameters entered into the AQFOR model. As was already indicated for the specific case of the stability class, the forecaster has some leeway in evaluating whether to use in the prediction a stability class projected from the meteorological tower data or substitute a stability class based on the synoptic forecast. This decision making is all part of the experience that the individual forecaster develops with time. There is also an element of conservative thinking that forecasters eventually incorporate, whether it is conscious or not.

Figure 4-2 shows the relationship of 1-hour average values of R_T to the number of hours from the time of forecast. It shows that as the time from the forecast increases the R_T rises, that is, the prediction becomes more and more conservative. This result is open to a great many interpretations. Over the period of the forecast, there is a tendency to expect the occurrence of the persistence of meteorological variables. When the meteorology is more variable than expected, the R_T is therefore higher. A second possible explanation would arise from the contention that the primary air quality concern at Kincaid, especially with only one unit running, is excursions above the 24-hour average standard. Periods of persistent meteorology are feared and perhaps predicted more often than they actually occur.

More specific and more accurate meteorological data appear to be needed to provide better inputs for the calculation of measured concentrations. A climatology that supplements the information derived from

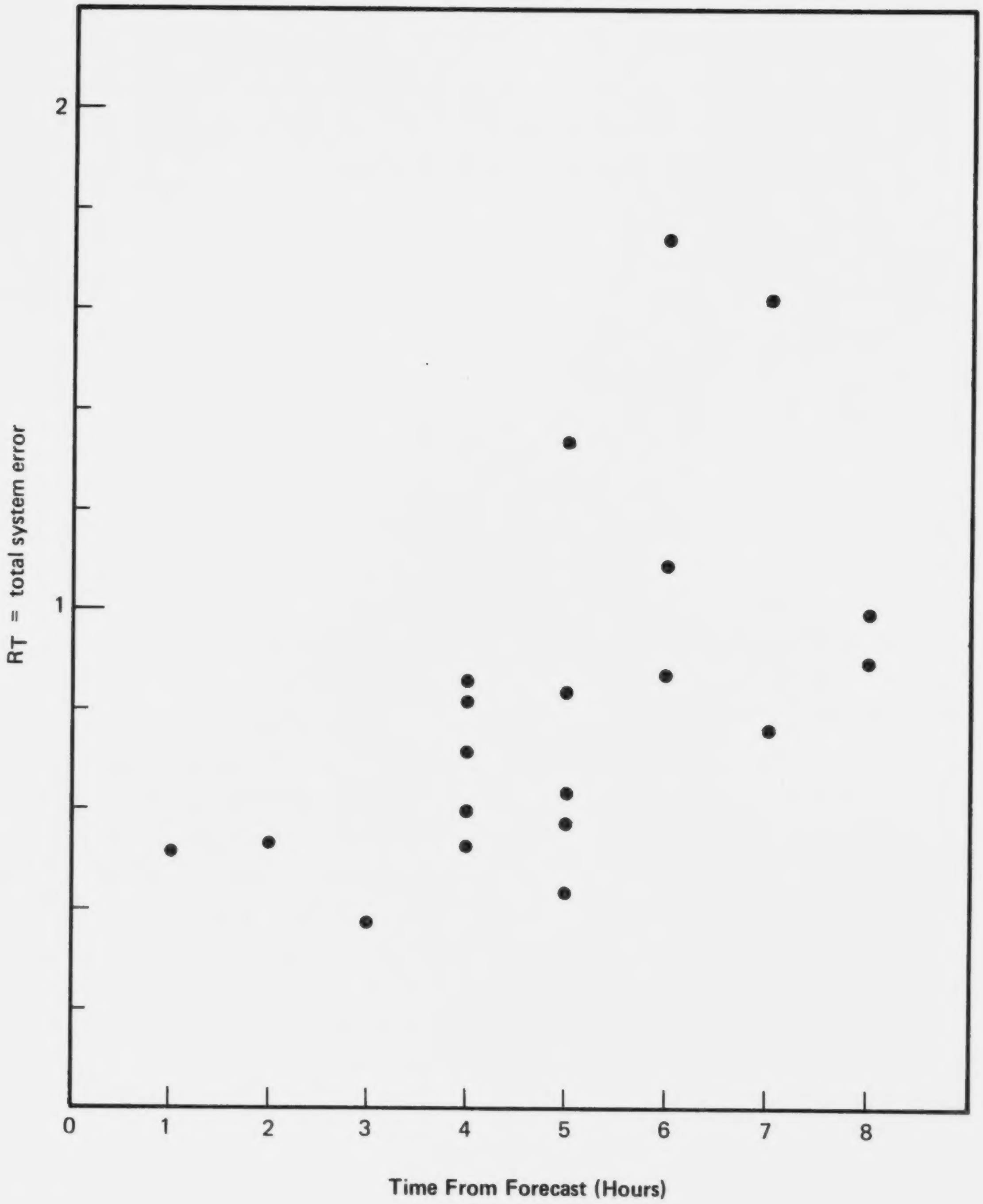

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Figure 4-2 Relationship of 1-Hour Average Values of R_T to Number of Hours from Time of Forecast

the synoptic weather situation with specific model input parameters would be useful in this regard. These parameters will then provide more accurate and reliable forecasts. Similarly, improvements made in the model must be made in the context of changes in the forecasting procedures. Improvements, especially with regard to mixing depth, could have a significantly beneficial effect on SCS performance.

5. RESULTS OF PROBABILITY ANALYSIS

5.1 Data Preparation and Processing

From the available data developed in the first portion of this study, it was necessary to derive a data input set for the model PROBL, which is described in detail in Appendix B. First the data set for which the PROBL analysis would be performed was defined. Without having the entire 24-hour times 123-day data set available, any frequency distributions that are analyzed will be skewed one way or another. It was decided that the Case 1 data are skewed toward low values of R_T and, therefore, represent the largest expected adverse error in the SCS. The selection of Case 1 will overestimate the possibility of exceeding the standards because it is skewed but will provide a meaningful example of the application of the reliability analysis system.

PROBL requires as input the frequency distributions of the variables Q(t), M(t) and R_T. The program needs each of these distributions as step functions with a set of defined classes and the probability of a value occurring in each class.

The classes for the values of Q(t) differ from the others in that they are percentages of the rated capacity of the source. In the case of Kincaid, there are two identical units of the same size. These units are not in simultaneous operation for most of the data set. (See Table 1-2). This fact allows for two different ways of analyzing the data: (1) assume 1,200 Mw is full load for the plant and take the percentage of time in each class relative to 1,200 Mw and (2) use only those hours with one unit operational and make the percentages of time in each class relative to 600 Mw. Table 5-1 shows the distributions of source emissions, Q(t), for each of the separate operating units at Kincaid and then for Options (2) and (1) above.

It is clear from this limited data set that when ground-level concentrations are high, the units that are operational are running just below full load. This is consistent with the fact that Kincaid is a base load plant. The last column, which shows all the hours relative to 1,200 Mw, is bimodal with a reasonable fraction of probability in the 1,020 to 1,140 Mw range and an even higher probability that one unit is operating in the 480 to 600 Mw range.

TABLE 5-1

FREQUENCY DISTRIBUTIONS OF Q

Class	Percentage of Mw Capacity	Percentage of Case 1 Hours in Each Class			
		Unit 1 600 Mw	Unit 2 600 Mw	1 Unit 600 Mw	2 Units 1,200 Mw
1	0-5	14.1	63.8	7.8	5.6
2	5-10	0.3	0.3	0.0	0.0
3	10-15	0.3	0.6	0.0	0.0
4	15-20	0.0	0.6	0.0	0.9
5	20-25	0.3	0.0	0.0	2.8
6	25-30	0.0	0.3	0.0	2.5
7	30-35	0.3	0.0	0.4	3.7
8	35-40	0.9	1.2	0.9	4.1
9	40-45	2.5	1.5	3.0	38.7
10	45-50	0.0	1.2	0.9	16.5
11	50-55	0.6	0.0	0.0	1.3
12	55-60	3.4	1.5	3.5	2.5
13	60-65	2.8	1.9	2.6	0.6
14	65-70	3.7	0.0	3.0	0.9
15	70-75	1.5	0.0	1.7	0.6
16	75-80	2.8	0.6	3.9	0.9
17	80-85	11.0	2.2	8.2	2.8
18	85-90	39.0	2.5	43.2	5.0
19	90-95	15.0	19.3	18.2	10.3
20	95-100	1.5	2.5	2.2	0.3

The next frequency distribution to be considered is that distribution for the meteorology, M(t). There are several ways to estimate the meteorological distribution frequency. The units of M(t) are concentration divided by emission rate. The two measures of concentration available to us are the observed and the predicted. Although a complete analysis of the distribution would include all maximum measured or predicted concentrations, the use of Case 1 for Q(t) requires the simultaneous use of only Case 1 hours. The measured concentration data set is more representative of actual meteorology and has been used.

One other effect needs to be accounted for in the preparation of the meteorology distribution. If a model were being used to develop the meteorology distribution, the source emissions could be set to some constant value. In the Kincaid example case, however, the emissions are different for each hour. The M(t) distribution based on the one unit Q(t) distribution has a relatively constant Mw load emission (as shown in Table 5-1), and it could be assumed that Q equals a constant. Otherwise, C_o could be divided by the emissions, Q_o, for each hour to derive an emission-weighted distribution. Values of Q_o have been normalized to 600 Mw or 1,200 Mw as appropriate. Where Q_o is equal to zero, that hour has been dropped from the distribution. These distributions are shown in Table 5-2 for the two-unit example and Table 5-3 for the one-unit example. The selection of Case 1 means there are no measured concentrations less than 0.05 ppm.

The distribution for C_o as shown in both M(t) tables is artificially bounded by the threshold value of 0.05 ppm. The distributions do vary downward when divided by Q_o but the shifts are not remarkable, as is to be expected for a base load plant.

The frequency distribution of R_T is straightforward, as it is derived from the analysis results in Section 4.2. Values of the R_T distribution by class are presented in Table 5-4. The heavy predominance of the lowest classes is expected from the results in Table 4-1.

The final parameter to be set for the running of PROBL is the threshold value at which a control action will be taken based upon a predicted concentration. Because this study is evaluating 1-hour average values, the selection of the 1- to 3-hour threshold actually used at Kincaid of 0.385 ppm is appropriate.

TABLE 5-2

FREQUENCY DISTRIBUTION OF M(t)
CASE 1, TWO-UNIT EXAMPLE

C_o		C_o/Q_o	
Class (ppm)	% of Hours	Class ($\frac{\text{ppm-sec}}{\text{gpm}}$)	% of Hours
0.000-0.029	0.0	0.000-0.024	1.9
0.030-0.059	21.2	0.025-0.049	0.5
0.060-0.089	44.6	0.050-0.074	27.2
0.090-0.119	15.6	0.075-0.099	25.3
0.120-0.149	7.8	0.100-0.124	10.7
0.150-0.179	5.2	0.125-0.149	12.7
0.180-0.209	1.3	0.150-0.174	5.1
0.210-0.239	1.3	0.175-0.199	7.0
0.240-0.269	1.3	0.200-0.224	1.9
0.270-0.299	0.0	0.225-0.249	1.9
0.300-0.329	0.4	0.250-0.274	1.9
0.330-0.359	0.0	0.275-0.299	0.9
0.360-0.389	0.4	0.300-0.324	0.5
0.390-0.419	0.0	0.325-0.349	0.0
0.420-0.449	0.4	0.350-0.374	0.5
0.450-0.479	0.0	0.375-0.399	0.0
0.480-0.509	0.0	0.400-0.424	0.0
0.510-0.539	0.0	0.425-0.449	0.5
0.540-0.569	0.0	0.450-0.474	0.0
0.570-0.599	0.4	0.475-0.499	0.0
		0.500-0.524	0.0
		0.525-0.549	0.0
		0.550-0.574	0.0
		0.575-0.599	0.5
		0.600-0.624	0.0
		0.625-0.649	0.0
		0.650-0.674	0.0
		0.675-0.699	0.5
		0.700-0.724	0.5
		0.725-0.749	0.0

TABLE 5-3

FREQUENCY DISTRIBUTION OF M(t)
CASE 1, TWO-UNIT EXAMPLE

C_o		C_o/Q_o	
Class (ppm)	% of Hours	Class $(\frac{\text{ppm-sec}}{\text{gm}})$	% of Hours
0.000-0.029	0.0	0.00-0.04	0.0
0.030-0.059	24.0	0.05-0.09	19.1
0.060-0.089	46.5	0.10-0.14	26.8
0.090-0.119	12.8	0.15-0.19	21.5
0.120-0.149	8.4	0.20-0.24	10.3
0.150-0.179	4.4	0.25-0.29	8.3
0.180-0.209	0.9	0.30-0.34	3.6
0.210-0.239	0.9	0.35-0.39	4.0
0.240-0.269	0.9	0.40-0.44	1.3
0.270-0.299	0.0	0.45-0.49	1.3
0.300-0.329	0.3	0.50-0.54	1.3
0.330-0.359	0.0	0.55-0.59	0.7
0.360-0.389	0.3	0.60-0.64	0.3
0.390-0.419	0.0	0.65-0.69	0.3
0.420-0.449	0.3	0.70-0.74	0.3
0.450-0.479	0.0	0.75-0.79	0.0
0.480-0.509	0.0	0.80-0.84	0.0
0.510-0.539	0.0	0.85-0.89	0.3
0.540-0.569	0.0	0.90-0.94	0.0
0.570-0.599	0.3	0.95-0.99	0.0
		1.00-1.04	0.0
		1.05-1.09	0.0
		1.10-1.14	0.0
		1.15-1.19	0.0
		1.20-1.24	0.0
		1.25-1.29	0.0
		1.30-1.34	0.0
		1.35-1.39	0.3
		1.40-1.44	0.3
		1.45-1.49	0.0

TABLE 5-4

FREQUENCY DISTRIBUTIONS OF R_T

CASE 1

Class R_T	1 Unit Example % Prob.	2 Unit Example % Prob.
0.00-0.34	43.7	38.6
0.35-0.69	17.8	13.7
0.70-1.04	16.0	14.0
1.05-1.39	11.3	9.4
1.40-1.74	5.6	7.2
1.75-2.09	3.9	6.9
2.10-2.44	0.0	4.0
2.45-2.79	0.0	2.2
2.80-3.14	0.9	2.5
3.15-3.49	0.0	0.3
3.50-3.84	0.4	0.6
3.85-4.19	0.0	0.3
4.20-4.54	0.0	0.0
4.55-4.89	0.0	0.0
4.90-5.24	0.0	0.0
5.25-5.59	0.0	0.0
5.60-5.94	0.0	0.0
5.95-6.29	0.0	0.0
6.30-6.64	0.0	0.0
6.65-6.99	0.4	0.3

5.2 PROBL Results

The results of PROBL calculations are provided in Table 5-5 for the one-unit example case and in Table 5-6 for the two-unit example case. A summary of the results in terms of percent of the time over the standard is shown in Table 5-7 along with the expected hours per 123-day period that they represent, that is percent of time over the standard multiplied by the 321 hours in Case 1. The results show that using the frequency distribution of observed concentration over actual emissions C_o/Q_o gives a higher expectation of exceeding the standard than using just the observed concentrations C_o. Division by Q_o does, as indicated above, stretch the frequency distribution upward and results in more hours of expected concentrations greater than the standard. The implied result, that the one-unit example results in a greater number of hours than the two-unit example, is anomalous. It occurs because the highest measured ground-level concentrations (on October 2, 1976) occurred with only one unit operating. In the two-unit example, those concentrations have a much lower probability of occurrence.

In general, these results point to the low frequency of expected excess of standards at the Kincaid Station. The example use of PROBL is for the worst-case distribution of highest observed concentrations and lowest average error ratio. In other words, Case 1 is the most severe test that could have been applied. When using C_o/Q_o, the expected frequency of exceeding the 3-hour standard of 0.5 ppm rises to three separate hours in the 123-day test period. That means that the SCS would on the average allow three 1-hour periods to exceed 0.5 ppm during any 123 days of operation. Those three hours would probably need to be consecutive to actually exceed the standard.

These results are biased by the discontinuous nature of the observed concentration distribution, especially near the 3-hour standard. More measurements in the range above 0.30 ppm for instance, would have better established the distribution and given more confidence that the PROBL results are representative of the tail of that distribution. This is a difficulty of applying the analysis to Kincaid where few measurements near the standard occur. Secondly, it is an argument for the hour-by-hour type of analysis that evaluates performance only for the worst-case situations, a specific requirement of standards to be exceeded no more than once per year.

TABLE 5-5

DISTRIBUTION OF PROBL RESULTS
CASE 1, ONE-UNIT EXAMPLE

C_o		C_o/Q	
Class* (ppm)	% Prob.	Class* (ppm)	% Prob.
0.000-0.029	10.768	0.000-0.024	9.962
0.030-0.059	26.614	0.025-0.049	7.290
0.060-0.089	36.692	0.050-0.074	27.136
0.090-0.119	15.444	0.075-0.099	24.687
0.120-0.149	4.747	0.100-0.124	10.344
0.150-0.179	1.990	0.125-0.149	6.295
0.180-0.209	1.291	0.150-0.174	6.314
0.210-0.239	0.987	0.175-0.199	1.903
0.240-0.269	0.115	0.200-0.224	1.542
0.270-0.299	0.296	0.225-0.249	1.365
0.300-0.329	0.223	0.250-0.274	0.906
0.330-0.359	0.135	0.275-0.299	0.206
0.360-0.389	0.194	0.300-0.324	0.253
0.390-0.419	0.094	0.325-0.349	0.137
0.420-0.449	0.007	0.350-0.374	0.065
0.450-0.479	0.016	0.375-0.399	0.251
0.480-0.509	0.033	0.400-0.424	0.108
0.510-0.539	0.175	0.425-0.449	0.046
0.540-0.569	0.082	0.450-0.474	0.034
0.570-0.599	0.000	0.475-0.499	0.064
		0.500-0.524	0.227
		0.525-0.549	0.110
		0.550-0.574	0.060
		0.575-0.599	0.052
		0.600-0.624	0.437
		0.625-0.649	0.091
		0.650-0.674	0.091
		0.675-0.699	0.011
		0.700-0.724	0.011
		0.725-0.749	0.000

*Maximum ground-level concentration

TABLE 5-6

DISTRIBUTION OF PROBL RESULTS
CASE 1, TWO-UNIT EXAMPLE

C_o		C_o/Q_o	
Class* (ppm)	% Prob.	Class* (ppm)	% Prob.
0.00-0.029	30.683	0.00-0.04	24.910
0.03-0.059	46.925	0.05-0.09	40.938
0.06-0.089	14.637	0.10-0.14	16.245
0.09-0.119	4.182	0.15-0.19	8.630
0.12-0.149	1.711	0.20-0.24	4.088
0.15-0.179	0.769	0.25-0.29	1.799
0.18-0.209	0.462	0.30-0.34	1.460
0.21-0.239	0.196	0.35-0.39	0.481
0.24-0.269	0.140	0.40-0.44	0.334
0.27-0.299	0.104	0.45-0.49	0.251
0.03-0.329	0.030	0.50-0.54	0.173
0.33-0.359	0.050	0.55-0.59	0.186
0.36-0.389	0.017	0.60-0.64	0.165
0.39-0.419	0.035	0.65-0.69	0.134
0.42-0.449	0.002	0.70-0.74	0.017
0.45-0.479	0.003	0.75-0.79	0.023
0.48-0.509	0.008	0.80-0.84	0.038
0.51-0.539	0.015	0.85-0.89	0.004
0.54-0.569	0.032	0.90-0.94	0.003
0.57-0.599	0.000	0.95-0.99	0.004
		1.00-1.04	0.002
		1.05-1.09	0.003
		1.10-1.14	0.011
		1.15-1.19	0.008
		1.20-1.24	0.030
		1.25-1.29	0.031
		1.30-1.34	0.032
		1.35-1.39	0.001
		1.40-1.44	0.000
		1.45-1.49	0.000

*Maximum ground-level concentration

TABLE 5-7

SUMMARY OF PROBL RESULTS

	One-Unit Example		Two-Unit Example	
M(t) Basis	% of Time Greater than 0.5 ppm	Hours Greater in 123 Days	% of Time Greater than 0.5 ppm	Hours Greater in 123 Days
C_o	0.257	0.82	0.055	0.18
C_o/Q_o	1.091	3.55	0.073	0.24

LIST OF REFERENCES

EPA 1976a. Technique for Supplementary Control System Reliability Analysis and Upgrading. OAQPS No. 1.2-037. EPA-450/2-76-015. U.S. Environmental Protection Agency.

EPA 1976b. Guidelines for Evaluating Supplementary Control Systems. OAQPS No. 1.2-036. EPA-450/2-76-003. U.S. Environmental Protection Agency.

ERT 1976. Determination of the Significant Inpact Area of the Kincaid Power Station. ERT Document P-1902. Environmental Research & Technology, Inc. Prepared for Commonwealth Edison.

APPENDIX A

DESCRIPTION OF THE AIR QUALITY FORECAST AND CONTROL DECISION MODELS

A.1 Overview

The Supplementary Control System (SCS) uses a computation model to predict the air quality at a field of points (receptors) in the vicinity of the plant and to select a plant operating schedule from a specified set of emission control actions. The Air Quality Forecast model (AQFOR) used to generate predictions of SO_2 is a state-of-the-art diffusion modeling program capable of handling multiple point source emissions. The input to AQFOR consists of the elements shown in Figure A-1. Calculations of past, as well as future, SO_2 values at receptor points, and actual past SO_2 observations at sensor locations are input to the Control Decision (CONDEC) model, which examines all running SO_2 averages to determine the plant operating conditions required to maintain three-hour and 24-hour SO_2 standards. The computations and information flow that yields the plant operating recommendations is also shown in Figure A-1.

The next section discusses the mathematics and physical assumptions used in AQFOR and the following sections describe the input and functioning for the AQFOR and CONDEC models.

A.2 AQFOR - Physical-Mathematical Description

A.2.1 Assumptions

The Air Quality Forecast (AQFOR) model combines calculation routines from various ERT models to provide a system best suited to the specific application and with the flexibility required for real-time operation in an emission limitation program. The component models generally include a multiple-source Gaussian diffusion model, a terrain model, and the ERT downwash model. Because the Kincaid plant is situated in nearly level terrain, and because the stacks are sufficiently high to prevent aerodynamic downwash effect by buildings or other structures in the area, terrain and downwash effects are not necessary in the model for this plant.

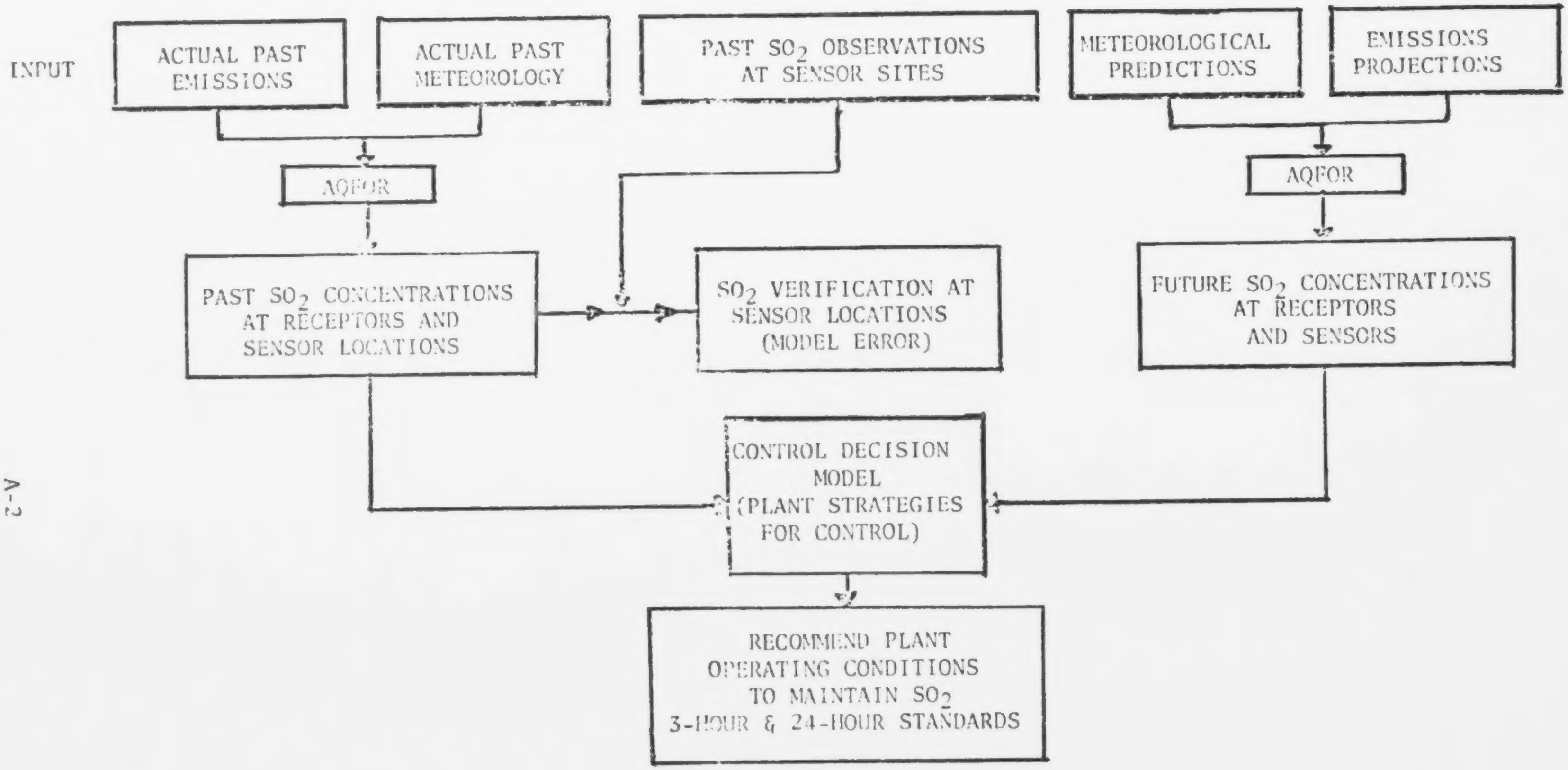
INPUT
ACTUAL PAST EMISSIONS
ACTUAL PAST METEOROLOGY
PAST SO_2 OBSERVATIONS AT SENSOR SITES
METEOROLOGICAL PREDICTIONS
EMISSIONS PROJECTIONS
AQFOR
AQFOR
PAST SO_2 CONCENTRATIONS AT RECEPTORS AND SENSOR LOCATIONS
SO_2 VERIFICATION AT SENSOR LOCATIONS (MODEL ERROR)
FUTURE SO_2 CONCENTRATIONS AT RECEPTORS AND SENSORS
CONTROL DECISION MODEL (PLANT STRATEGIES FOR CONTROL)
RECOMMEND PLANT OPERATING CONDITIONS TO MAINTAIN SO_2 3-HOUR & 24-HOUR STANDARDS

Figure A-1 Input, Calculations, and Information Flow for SCS Plant Operating Recommendations

The specific model of the Kincaid plant is a steady-state Gaussian plume model capable of incorporating multiple sources.

The model assumes that meteorological conditions are uniform over the region and steady conditions apply for time periods of one-hour duration. This assumption is appropriate for Kincaid for the following reasons:

1) In relatively flat terrain, systematic large-scale spatial variations in wind speed, direction, and atmospheric stability conditions are generally not expected. Variations which do occur are highly unpredictable, and when averaged over periods of time of an hour or more will tend to cancel.

2) The downwind region of maximum ground level impact for the Kincaid plant is expected to be well within twenty kilometers for nearly all meteorological conditions and substantially shorter distances for high wind speed conditions. Thus, travel times for stack emissions to reach the region of maximum impact will be generally less than one hour. More likely, travel times for periods of SCS curtailment activities will be of the order of 10 to 15 minutes. Under these circumstances, since hourly-averaged wind data represents a reasonable lower limit on the time resolution of meteorological input data, no improvement of accuracy can be obtained by using other than a steady-state plume model. Time-dependent models are appropriate only when the travel time to the region of interest is larger than meaningful time or spatial scales associated with changes in meteorological conditions, for example, in situations involving complex terrain.

The use of a steady-state Gaussian model results in substantial savings of computation time and computer memory requirements. These savings permit the use of more sophisticated data reduction and analysis and data presentation procedures.

The models are described in more detail in the following sections.

A.2.2 Plume Model

Calculations performed in the model involve multiple applications of the Gaussian plume equation, which represents the concentration pattern downwind from a point source. The general form of the equation for the coordinate system presented in Figure A-2 is:

$$\chi(0,0,z) = \frac{q(x,y,H)}{2\pi\sigma_y\sigma_z u} \exp\left[-1/2 \left(\frac{y}{\sigma_y}\right)^2\right] \cdot \left(\exp\left[-1/2 \left(\frac{z-H}{\sigma_z}\right)^2\right] + \exp\left[-1/2 \left(\frac{z+H}{\sigma_z}\right)^2\right]\right) \qquad (1)$$

where

χ = SO_2 concentration

(x,y,z) = the respective upwind, crosswind and vertical components of a Cartesian coordinate system, such that the receptor point is located at or vertically above the origin (expressed in units of length) and the source at the point (x,y,H).

H = the effective height of emission and, therefore, the centerline height of the plume (length)

q = the source strength (mass/time)

σ_y, σ_z = dispersion coefficients that are measures of crosswind and vertical plume spread. These two parameters are functions of downwind distance and atmospheric stability (length)

u = average wind speed (length/time)

The source base is at $z = 0$ in the coordinate system, and the plume centerline reaches the equilibrium height H at some distance downwind from the source. The most important assumptions upon which the equation is based are the following:

1) The wind speed and direction in the vicinity of the point source are constant throughout the period of interest. The wind speed, however, is specified as an increasing function of height.

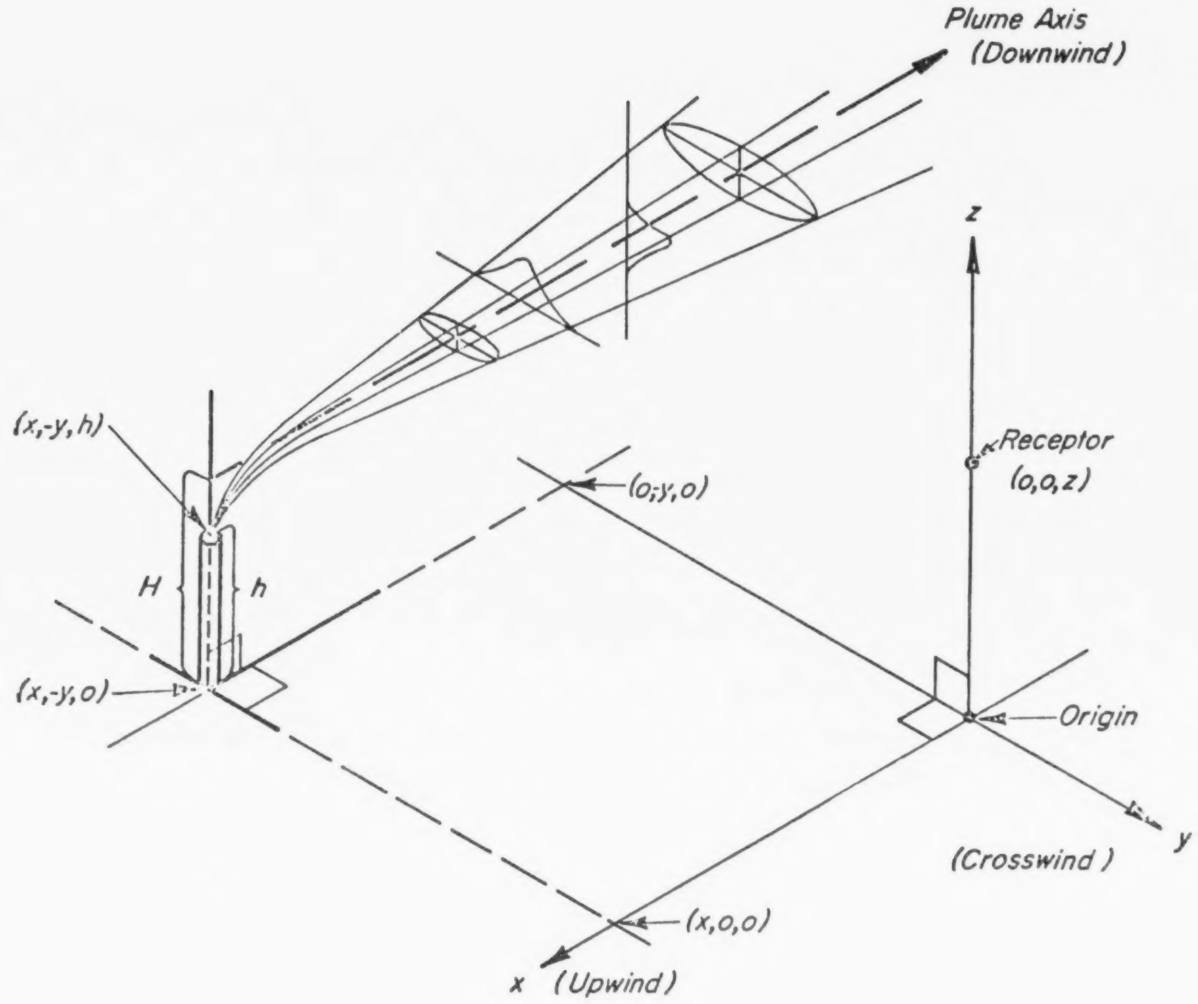
Plume Axis
(Downwind)
z
(x,-y,h)
Receptor
(o,o,z)
(o,-y,o)
H
h
(x,-y,o)
Origin
y
(Crosswind)
(x,o,o)
x (Upwind)

Figure A-2 Coordinate System Showing Gaussian Distributions in the Horizontal and Vertical

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2) When the effluent enters the atmosphere, the plume rises until it reaches an equilibrium altitude; the plume centerline height remains constant at all downwind distances.

3) At any downwind distance, the maximum concentration occurs at the plume centerline. The distribution of concentration values off the centerline is given by the product of two Gaussian, or bell-shaped, curves.

4) The concentration profiles described by the Gaussian form are not instantaneous plume profiles. Instead they represent concentrations averaged over one hour.

5) None of the effluent is lost from the plume. Therefore, when the plume intersects the ground surface, it is assumed that all material is reflected back above the ground.

6) The effluent rate is constant, and the meteorological parameters determining plume geometry are constant.

The actual computation of concentrations from heat and SO_2 emission rates has two steps:

1) Computations of the effective release height (or plume rise) H from the heat rate P and the meteorology.

2) Computation of the ground-level concentrations given H and the SO_2 emission rate Q.

The plume rise is calculated using Briggs' transitional plume rise equations (Plumerise by Gary Briggs, AEC Critical Reviews, 1971):

$$H = SHT + \Delta H$$

where SHT = stack height (meters)

and where ΔH is calculated according to the following equations:

$$\Delta H = 1.6\ F^{1/3}\ (\min(x,\ 3.5\bar{x}))^{2/3}/u$$

for stabilities 1, 2, 3, and 4

$$\Delta H = 1.6\ F^{1/3}\ x^{\ 2/3}/u$$

for stability 5 when $u > 1.37$ m/s
and $x < 2.4\ u/S^{1/2}$

$$\Delta H = 2.9\ (F/(S.u))^{1/3}$$

for stability 5 when $u \geq 1.37$ m/s
and $x \geq 2.4\ u/S^{1/2}$

$$\Delta H = 5.0\ F^{1/4}/\ S^{2/8}$$

for stability 5 when $u < 1.37$ m/s

where

F = buoyancy flux of stack emissions (m^4/s^3)
= $8.8432.10^{-6} \cdot P$,
P = Heat rate (Watts),
x = down wind distance (m)
$\bar{x}$ = down wind distance at which atmospheric turbulence dominates entrainment in plume rise (m)
= $\min\ (14.F^{5/8},\ 34.49.F^{2/5})$
u = stack top wind speed (m/s)
= $u_o(SHT/ZWIND)^{EPS}$
u_o = reference wind speed (m/s)
ZWIND = height at which reference wind speed measured (m),
EPS = stability dependent wind profile parameter,
S = square of the Brunt-Väisälä frequency,
= $VPTG.g/TA$
VPTG = vertical potential temperature gradient (°K/m)
g = acceleration due to gravity (m/s^2)
= $9.8\ m/s^2$
TA = ambient temperature (°K).

Once plume rise H is calculated, the ground-level concentrations are calculated in the following way:

$$\chi_{TOT} = \chi + \chi_{BACK}$$

where

χ = computed concentration at the receptor due to the stack and the meteorology,

and

χ_{BACK} = contribution of background sources (as a function of only the meteorology and not the receptor location).

If the plume rise H is greater than DMX + 50.0 meters, where DMX is the mixing lid, then the plume is considered to have punched through the region where effective mixing takes place so $\chi = 0$.

If the plume rise H is less than DMX + 50.0 it is set to DMX if it exceeds DMX. Then χ is computed as the sums of two terms

$$\chi = Q. \ [(1-f).G + f.D]/u$$

where

f = fraction of the plume that is entrained by the building wake,
G = Gaussian dispersion of effluent outside wake,
and D = non-Gaussian dispersion of effluent inside building wake.

The fraction f is set to 0 if building downwash is not to be considered by the plant. Otherwise the fraction f is computed in terms of an interaction parameter I,

$$f = \exp\ (4.\max\ (0,\ 1-I))$$

where

I = SHT + 300. LB/(1.7.HBE)
HBE = effective building height (for the given wind direction and stack) (m)

LB = buoyancy length (m)
$= F/(1.15 * u)^3$

(with F = buoyancy flux, u = stacktop wind speed as above).

The Gaussian dispersion term G is calculated by the formula

$$G = hdf \cdot vdf$$

where

hdf = a horizontal dispersion
vdf = a vertical dispersion.

The vertical dispersion is the multiple reflected Gaussian of Turner's Workbook (pg. 36):

$$vdf = \frac{1}{\sqrt{2\pi}\,\sigma_z} \left(1 + 2. \sum_{j=1}^{\infty} e^{-1/2 \left(\frac{2j\,D-H'}{\sigma z}\right)^2}\right)$$

where σ_z is a stability-dependent dispersion coefficient

$$\sigma_z = AZ \cdot X^{BZ} + CZ,$$

and where D and H' are the mixing lid and plume heights adjusted for terrain by the formulas

$D = DMX - \Delta$

$H' = H - \Delta$

$\Delta = (1-T.) \min (H, THT)$

T. = a stability-dependent terrain correction parameter

THT = terrain height (relative to stack base) in meters.

The horizontal dispersion term averages the standard Gaussian over a sector to account for wind variability:

$$hdf = \begin{cases} \dfrac{1}{x^*S}\ \mathrm{erf}\left(\dfrac{x^*S}{2\sqrt{2}\ \sigma_y}\right) & \text{if } |y| \leq x^*S/_2 \\ \dfrac{1}{2.x^*S}\left(1-\mathrm{erf}\left(\dfrac{x^*S}{2\sqrt{2}\ \sigma_y}\right)\right) & \text{if } x^*S/_2 < |y| \leq \dfrac{3x^*S}{2} \\ 0 & \text{otherwise} \end{cases}$$

where

y = crosswind distance (m)

σ_y = a stability-dependent horizontal dispersions coefficient

$= AY.x^{BY} + CY,$

and S = sector width (radians)

The sector width is allowed to vary by forecast period to account for increasing uncertainty of forecast wind direction.

The non-Gaussian dispersion term D is taken to be 0 at receptors that are not on the downwind side of the source. For receptors downwind, D is computed by

$$D = hdf.vdf$$

where the horizontal dispersion is a 22-1/2 sector average

$$hdf = \frac{1}{S\ .398x + WIDTH}$$

(where WIDTH is an initial mixing width in meters)
and the vertical dispersion vdf is given by

$$vdf = \left(1-\exp\left[-.0015\ (x/HBE)^3 (u/18.)^4\right]\right)/HW$$

where $HW = \max\ (\bar{\sigma}_z,\ (HBE^3 + 125.x)^{1/3})$

and $\bar{\sigma}_z = 1.25.CAZ.x^{CBZ} + CCZ$.

A.2.3 Receptor Grid

The receptor points at which the AQFOR model predicts concentrations are carefully chosen to provide a non-biased input for the control decision model. For the Kincaid plant, a radial receptor grid forming concentric circles about the plant accomplishes this purpose. Additional receptor points are placed to coincide with the monitoring sites.

If a rectangular grid is chosen, receptors will not lie at equal distances from the power plant for all wind directions. Thus for the same meteorological and plant conditions, but different wind directions, a critical concentration may be predicted in one wind sector but not another. This would bias control actions for certain wind sectors.

With the radial receptor grid, seven receptors along each of 16 radials, plus the monitoring receptors, yields a total of 122 receptor points. The specific radius of each concentric receptor circle is determined by the significant impact area of the plant. The distances and number of receptor circles necessary for proper coverage can be readily modified as experience in operating the Kincaid SCS system accumulates.

A.3 AQFOR and CONDEC - Functional Program Description

The SCS computer program involves three phases, and there is one module for each phase:

1) EMFOR (for EMissions FORecast) which, based on observed and projected loads, computes plant SO_2 emissions, for each specified plant operating schedule specified by the emissions control strategy.

2) AQFOR (for Air Quality FORecast) which, based on observed and predicted meteorological conditions and on estimated emissions, computes SO_2 concentrations at each of the receptor points on a radial grid centered at the plant for each specified operating schedule, and

3) CONDEC (for CONtrol DECision) which examines the SO_2 concentration sequence, for each receptor and operating schedule, and selects a plant operating schedule, if possible which maintains various SO_2 average concentrations including, in particular, the 24-hour and three-hour averages, below specified thresholds, at each of the receptors.

The purpose of the SCS program is to project for 24-hours in the future, the forecast period, and to select an operating schedule which maintains air quality. The Control Decision procedure requires an historical operating schedule for that period of the immediate past which is equal in length to the forecast period. This hindcast period, together with the forecast period, forms the basic time sequence examined by the three phases: EMFOR, AQFOR, and CONDEC.

A.3.1 The Emissions Forecast (EMFOR)

A.3.1.1 Components of the Emissions Forecast

EMFOR has, itself, three phases:

1) The translation of projected loads and plant operating schedules into a set of candidate operating schedules for the forecast period by means of a control strategy. This strategy describes alternative operational modes which include possible departures from the projected (and desired) operations schedule;

2) the calculation of SO_2 emissions for each alternative operating mode for the forecast period; and

3) the calculation of SO_2 emissions for the hindcast period based on the actual operating schedule for that period, and updated by observed emissions when these are available.

All three of these phases use detailed data on the plant configuration, together with current information on capacities and fuels.

The air quality calculations require, for each stack, the emission rates

P = stack gas sensible heat (watts)

and Q = stack SO_2 emission rate (gm/sec).

These numbers are computed from the unit loads based on the inputs.

Unit Specific:

C1 = heat rate constant 1, Watts/(load unit)

C2 = heat rate constant 2, Watts/$(\text{load unit})^2$

T1 = exit temperature constant 1, Kelvin
T2 = exit temperature constant 2, Kelvin/(load unit)
EFF = unit efficiency, percent
AF = flue gas to fuel ratio.

Fuel Specific:

SPC = fuel sulfur content, percent
HHV = higher value of fuel, jouls/gm
A = fuel-specific AF adjustment

Plant Specific:

TA = ambient temperature, Kelvin.

With these inputs, the program computes for each unit

1. The heat rate, HR, in Watts/(load unit)
   $HR = C1 - C2 * LOAD$
2. The heat input rate, HIR, in Watts
   $HIR = HR * LOAD/(EFF * 0.01)$
3. The exit temperature, TS, in Kelvin
   $TS = T1 + T2 * LOAD$
4. The flue gas rate, FGR, in g/sec
   $FGR = HIR * AF * (1 + A)/HHV.$
5. The SO_2 emission rate, SO_2, in g/sec
   $SO_2 = 2. *HIR *(SPC * .01)/HHV.$

Summing overall units feeding a stack, the program then computes the totals for each stack

1. The total heat input rate, SHIR, in Watts
   $SHIR = SUM(Unit\ HIR)$
2. The total flue gas rate, SFGR,
   $SFGR = SUM(Unit\ FGR),$
3. The weighted average exit temperature, STS, in Kelvin
   $STS = SUM(Unit\ TS * FGR)/SFGR$
4. The total SO_2 emissions, Q, in g/sec
   $Q = SUM(Unit\ SO_2).$

From these data, the stack gas sensible heat P, in Watts, is computed as

$$P = 1.00417 * SFGR * (STS-TA).$$

If Stack Gas Analyser data are available then P and Q are calculated as

$$P = 9.8339E-3 * TFGR * (T-288.89)$$

and $Q = 1.2672E-8 * SO_2\ SHIR/CO_2$

where

TFGR = flue gas rate, in SCF/sec,

= $0.605956 * SHIR/CO_2$

T = stack temperature reading (°K)

SO_2 = stack SO_2 reading (ppm)

and CO_2 = stack CO_2 reading (percent).

A.3.1.2 The Control Strategy and Its Translation Into Alternative Operating Schedules

The preliminary control strategies developed for the Kincaid SCS program can be found in Appendix B and consist of a succession of steps, in order of increasing severity, that may be taken to rearrange loads and alter the emissions pattern. Each step is a sequence of possible changes selected from the permissible operations, e.g.:

TRANSFER a specified load FROM unit to "GRID",

TRANSFER ALL of the load on a specified unit TO "GRID", and

SET a specified unit to operate at a specified load.

Where it makes sense in the above operations, a fictitious unit named GRID may be specified to represent the transfer of load to or from an external source.

The control strategies are designed to be realistic variations from the projected schedule and are intended to reduce the adverse impact of plant emissions on air quality.

To translate a control strategy into a set of alternative operating schedules, EMFOR requires as input, for each time interval of the forecast period:

the maximum capacity of each unit,
the projected load on each unit,
the minimum capacity of each unit, and
the intended fuel for each unit.

The projected loads and fuels become the initial operating schedule for the forecast period. The remaining operating schedules are generated by going through the steps of the control strategy, in the order given, and modifying the existing schedule to generate the new schedule. Thus step 1 of the control strategy transforms schedule 1 (the projected schedule) into schedule 2, step 2 transforms schedule 2 into schedule 3; and so on until the steps are exhausted.

The new schedules obey the following rules:

a) no unit may operate above its maximum capacity, and

b) no unit may operate below its minimum capacity,

unless ALL of its load is transferred. In this last case the load on the unit is set to zero.

A.3.1.3 EMFOR: Generation of SO_2 Emissions from Operating Schedules

Calculation of SO_2 emissions for the hindcast period and the forecast period differ in only two respects: there is only one schedule for the hindcast period, the actual schedule; and past emissions is updated using observed emissions when the data is available.

For each schedule and each time interval, EMFOR has already determined the load and fuel of each unit. From the load, unit efficiency and turbine efficiency, EMFOR calculates that heat needed to support that load. Again using the unit efficiency, EMFOR calculates the heat coming out of the associated stack. Using the needed heat and the heat content of the fuel being used, the amount of fuel consumed is computed. From the fuel consumption, and the sulfur content of the fuel, the rate of SO_2 emission from the stack is calculated.

The heat output and SO_2 emission rate are summed for each stack and transmitted, to AQFOR for the air quality forecast.

A.3.2 The Air Quality Forecast (AQFOR)

Corresponding to the two time periods, hindcast and forecast, there are two phases to AQFOR:

1) the historical phase, which uses actual observed meteorological conditions to generate past SO_2 concentrations at the specified receptor locations. These estimates are updated using observed SO_2 concentrations for those receptors corresponding to monitoring sites.
2) the forecast phase, which uses a predicted meteorological condition to specify predicted SO_2 concentrations at receptor locations.

The calculation of SO_2 concentrations at the receptor sites is the same for both periods. For each time interval and each schedule, the source description calculated by EMFOR is used by AQFOR to estimate the SO_2 concentrations.

Based on the weather condition (wind speed, wind direction, stability, and mixing depth) and the source description (heat output, exit velocity, location, height, diameter) AQFOR uses the Gaussian dispersion model (Section A.2) to calculate the contribution at each receptor due to the SO_2 emissions from the stacks. To these calculated concentrations, AQFOR adds the background concentrations due to other SO_2 emission sources in the area.

The concentrations for each receptor are then transferred to CONDEC for the control decision phase.

A.3.3 Control Decision Model (CONDEC)

A.3.3.1 Control Action Criteria

The interaction of observed conditions, predicted conditions and air quality standards produces recommended actions designed to result in compliance with these standards. The model operates in real-time, making use of two distinct dynamic forms of information.

1) predicted air quality based on observed and forecast meteorology and plant operating conditions, and observed past and current air quality.

2) predicted air quality based on currently observed trends in air quality.

If either form of information indicates an actual, impending or potential SO_2 level above those given by a threshold values for different time periods (Figure A-3) of any applicable standard, the control decision model recommends an adjustment to the operations schedule.

The criteria for specifying control actions are the following:

1) The action must be effective in keeping SO_2 concentrations below threshold values, i.e., the control decision model recommends measures which will reduce ambient SO_2 concentrations below threshold levels, thus emissions are reduced as required, including complete shutdown, if necessary.

2) The order in which control measures are applied must be consistent with plant operations requirements, safety, and economic considerations. In the latter case, for cutback alternatives, the one chosen must be the one producing the minimum cost penalty to the plant.

3) The parameters which define the model - i.e., the control strategy - must be easily modified to accommodate changes in plant operating requirements.

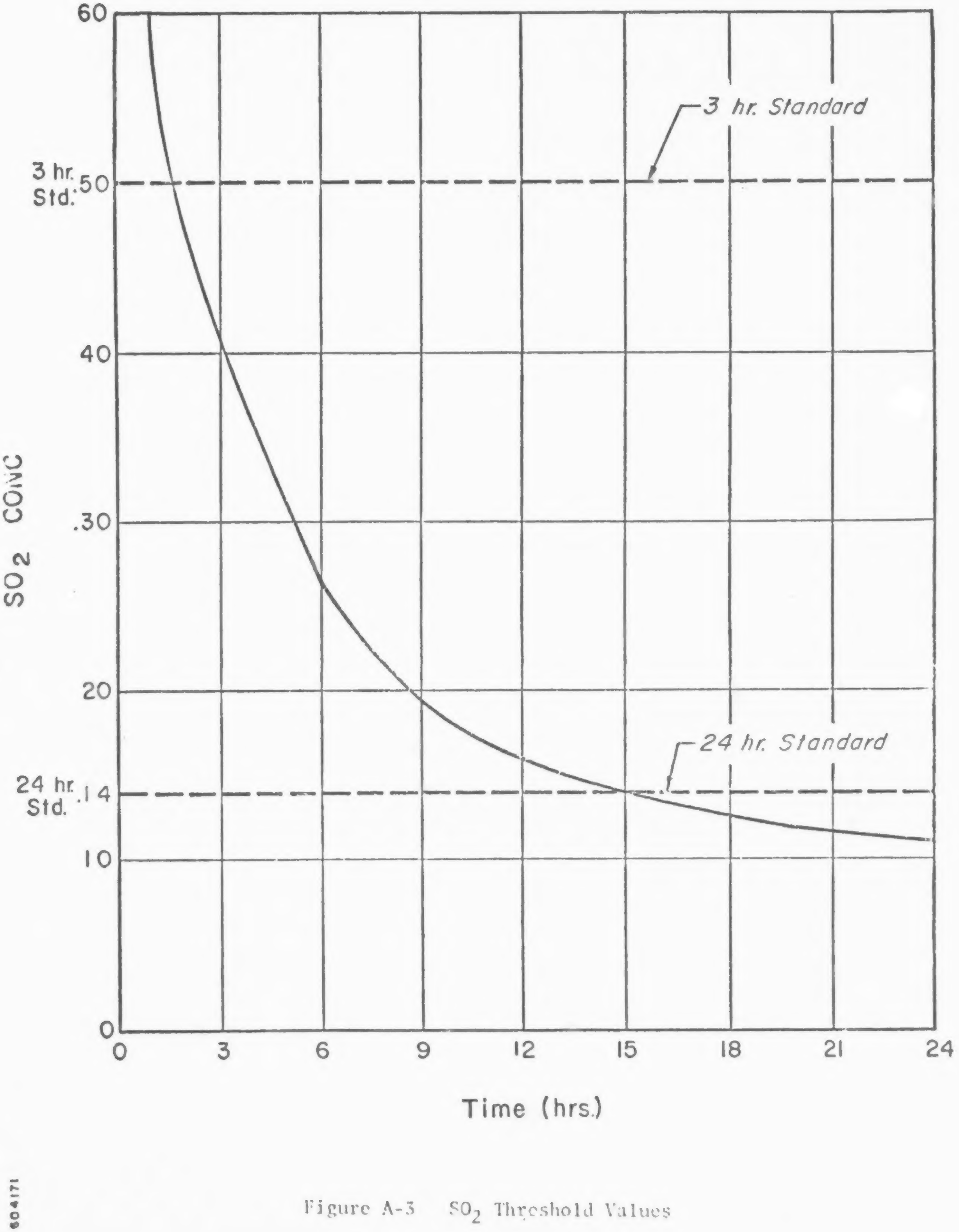

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Figure A-3 SO_2 Threshold Values

4) The control measures, while providing a margin of safety, must not be so conservative as to unnecessarily cut back or shutdown operations.

5) The application of control measures as a function of time must occur in a smooth, stable manner, avoiding short-term changes which are impractical from an engineering point of view.

The Control Decision Model (CONDEC) has been developed with these criteria in mind. A brief discussion of the theory and algorithms of the control decision model is given in the following section.

A.3.3.2 Model Theory

A.3.3.2.1 Algorithm Description

CONDEC makes use of a three-dimensional computation space referred to as the C-K-T (concentration vs. cutback vs. time) space. AQFOR computes for each receptor the array of concentrations C (K,T) for time periods T = 1, 24 and operating modes K = 1, N, where K= 1 consists of the most desirable total plant configuration, and the ordering K = 2, ..., N corresponds to successive schedule modifications. These concentrations shall for this discussion be regarded as instantaneous, that is one hour is the smallest time increment permitted in the system.

The concentrations may be represented in a three dimensional space, which we shall call the C-K-T diagram, as shown in Figure A-4. If a surface is passed through the points in this space, one obtains the representation of Figure A-5, which shows isopleths of concentration above the value referred to as the instantaneous or (one-hour) cutback concentration. (In the diagram, this value is the three-hour standard 0.5 ppm. A value less than 0.5 ppm can be selected to provide a safety factor.) The shaded area is thus inaccessible, since it is above some unacceptable threshold value for this receptor.

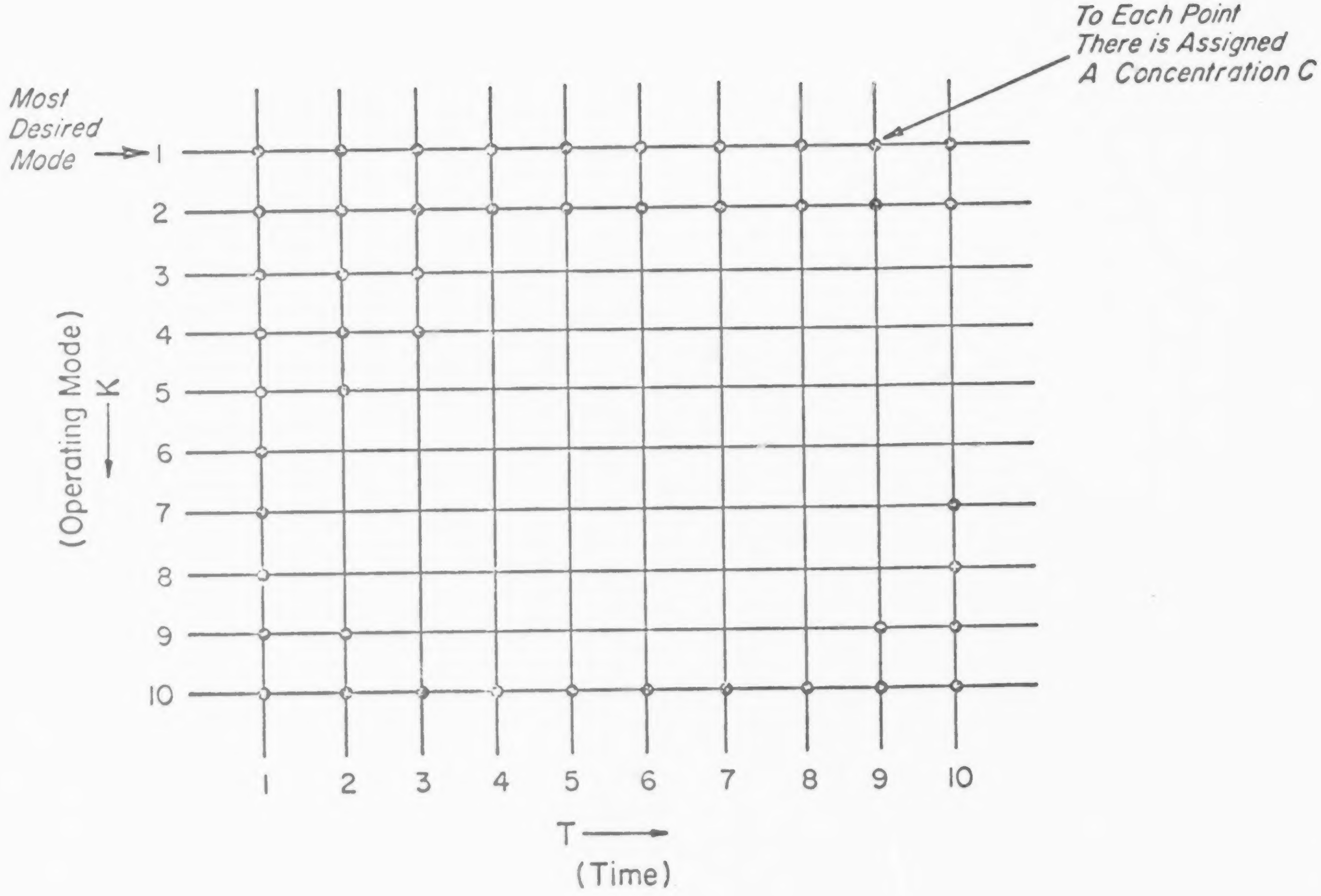

To Each Point
There is Assigned
A Concentration C
Most
Desired
Mode
1
2
3
4
5
6
7
8
9
10
(Operating Mode)
K
1
2
3
4
5
6
7
8
9
10
T
(Time)

Figure A-4 C-K-T Diagram for one Receptor Represented as an Array of Discrete Points. Shown are possible ordered operating modes (9 stages of cutback) and 10 time periods.

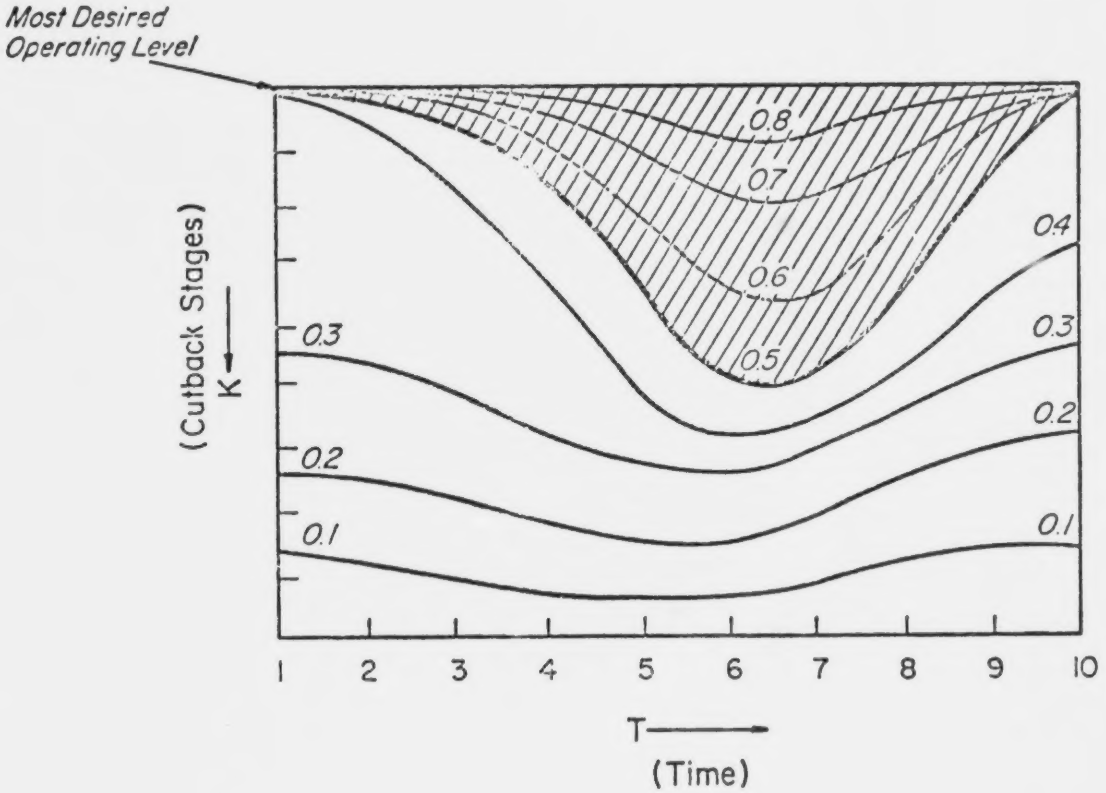


Figure A-5 C-K-T Diagram for one Receptor Represented as a Surface. The shaded area represents all operating modes yielding 3-hour concentrations in excess of 0.5 ppm.

For each receptor, there is a similar C-K-T diagram which may contain within it an inaccessible region. If all such diagrams are superimposed, as shown in Figure A-6, the result becomes the inaccessible region for the entire plant. This diagram defines the set of operating modes which is inaccessible for at least one receptor - with respect to 1-hour average concentrations. Any projected plan of operation for the plant may be represented as a line along the surface of the C-K-T diagram. The plan is therefore viable with respect to the instantaneous (1-hour averaged) concentrations if and only if this line path does not enter the plant inaccessible region.

Extension to averages of concentration performed over multiples of the fundamental 1-hour period requires the added consideration of the history of actual concentrations. The running average of period P, beginning at time T_o is given for a single receptor by:

$$A(P,T_o) = \frac{1}{P}\left\{ \int_{T_o}^{0} C_o(T')dT' + \int_{0}^{P+T_o} C(K',T')dl' \right\}, \qquad T_o \leq 0$$

$$A(P,T_o) = \frac{1}{P} \int_{T_o}^{T_o+P} C(K',T')dl' , \qquad T_o > 0 \qquad (6)$$

where $C_o(T)$ is the one-hour averaged concentration observed for this receptor at time T ($T \leq 0$) and the integral for $T > 0$ is a line integral performed along the projected plant operation path. For each averaging period P, there is a control decision threshold value $A_{max}(P)$ as shown for example in Figure A-3. The requirement for viability of any projected plan with respect to the averaging period P is thus

$$A(P,T_o) < A_{max}(P) \qquad (7)$$

for all values of T_o on the range -P to 24-P. Using Equation (6), this requirement becomes

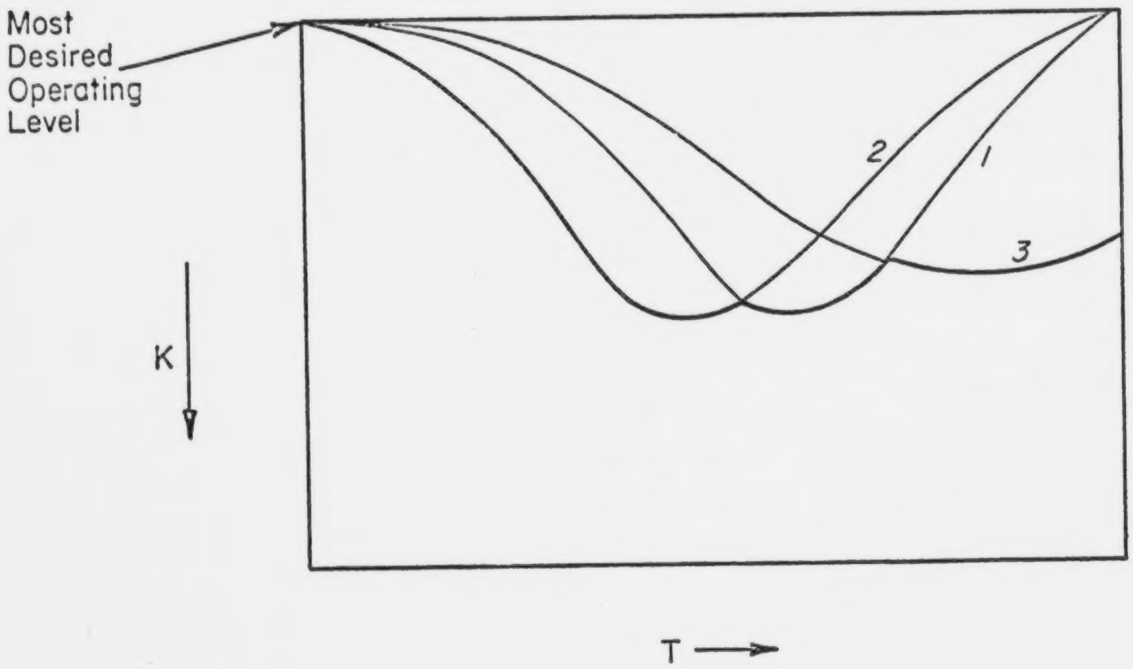


Figure A-6 Composite K-T Diagram for a 3-Receptor System. The overall plant inaccessible region is that which includes any inaccessible region for a single receptor (heavy line)

$$\frac{1}{P}\int_{0}^{P+T_o} (C(K',T')dl' < A_{max}(P) - \frac{1}{P}\int_{T_o}^{0} C_o(T')dT', \quad T_o \le 0$$

$$\frac{1}{P}\int_{T_o}^{P+T_o} C(K',T')dl' < A_{max}(P) \qquad , \ T_o > 0 \qquad (8)$$

The path integrals defining the projected plan of operation must satisfy the dual requirements of compensating for past occurrences, while protecting against future occurrences.

Define $C_{Test}(P,T_o)$ as that constant concentration which, if maintained everywhere along the path would just equal the effective control threshold as given by Equation (8). Thus

$$C_{Test}(P,T_o) = \frac{1}{P+T_o}\left\{ P \cdot A_{max}(P) - \int_{T_o}^{0} C_o(T')dT' \right\} \quad , \ T_o \le 0$$

$$C_{Test}(P,T_o) = A_{max}(P) \qquad , \ T_o > 0 \qquad (9)$$

Then, Equation (8) becomes

$$\frac{1}{P}\int_{max(0,T_o)}^{P+T_o} \left\{ C(K',T') - C_{Test}(P,T_o) \right\} dl' < 0 \qquad (10)$$

Thus, if the values of C_{Test} are known, the necessary and sufficient condition for viability of a projected plan with respect to a given receptor is that C must be less than C_{Test}, averaged over the path. One sufficient condition is that $C(K',T') < C_{Test}$ for all points on the projected path. This would be unnecessarily restrictive however, since it would limit operations to those modes for which concentrations are always less than the control decision threshold for the longest averaging period (e.g., the 24-hour standard of 0.14 ppm from Figure A-3).

It is important to note, however, that even if the above condition is not applicable everywhere on a projected path it must be true on the average over the path. Figure A-7 represents a simple example for the case in which concentrations are constant with T. Application of the one-hour criterion defines the accessible region for this receptor to paths below A-A" in Figure A-7. Economic considerations thus make the path A-A" the best first choice for a projected path, subject to maintenance of long-term average criteria.

In the example shown, the quantity C_{Test} is assumed to be 0.4 ppm for the averaging period P. The conditions of Equation (10) make it impossible for the first choice level 0.5 ppm to be maintained for the entire period; hence a revised path A-A'-B'-B" is indicated. Note that the path shown in Figure A-7 is one of an infinite set of choices which may satisfy the condition of Equation (10), subject only to the requirement that the area between the path and C_{Test} before the cutback A'-B' must equal that after the cut. From the foregoing discussion it is clear that, if the concentration at any point along a projected plant-operations path exceeds the value of C_{Test} for any averaging period P and initial time T_o, a cutback will have to be made to satisfy Equation (10).

The algorithm for computation thus consists of the following:

1) Compute the C(K,T) array for each receptor (AQFOR);

2) Identify the inaccessible area for each receptor as that for which the instantaneous (one-hour averaged) concentrations exceed the one-hour threshold.

3) Identify the overall plant inaccessible area as the area which is inaccessible for one or more receptors.

4) Define the initial first choice projected path as that which produces minimum cutback and remains in the plant accessible area.

5) Compute the quantities $C_{Test}(P,T_o)$ using Equation (9).

6) For each receptor in sequence, and beginning with the earliest value of T_o and moving forward, apply the test of Equation (10) for each period P under consideration, modifying the path as required to meet the criterion.

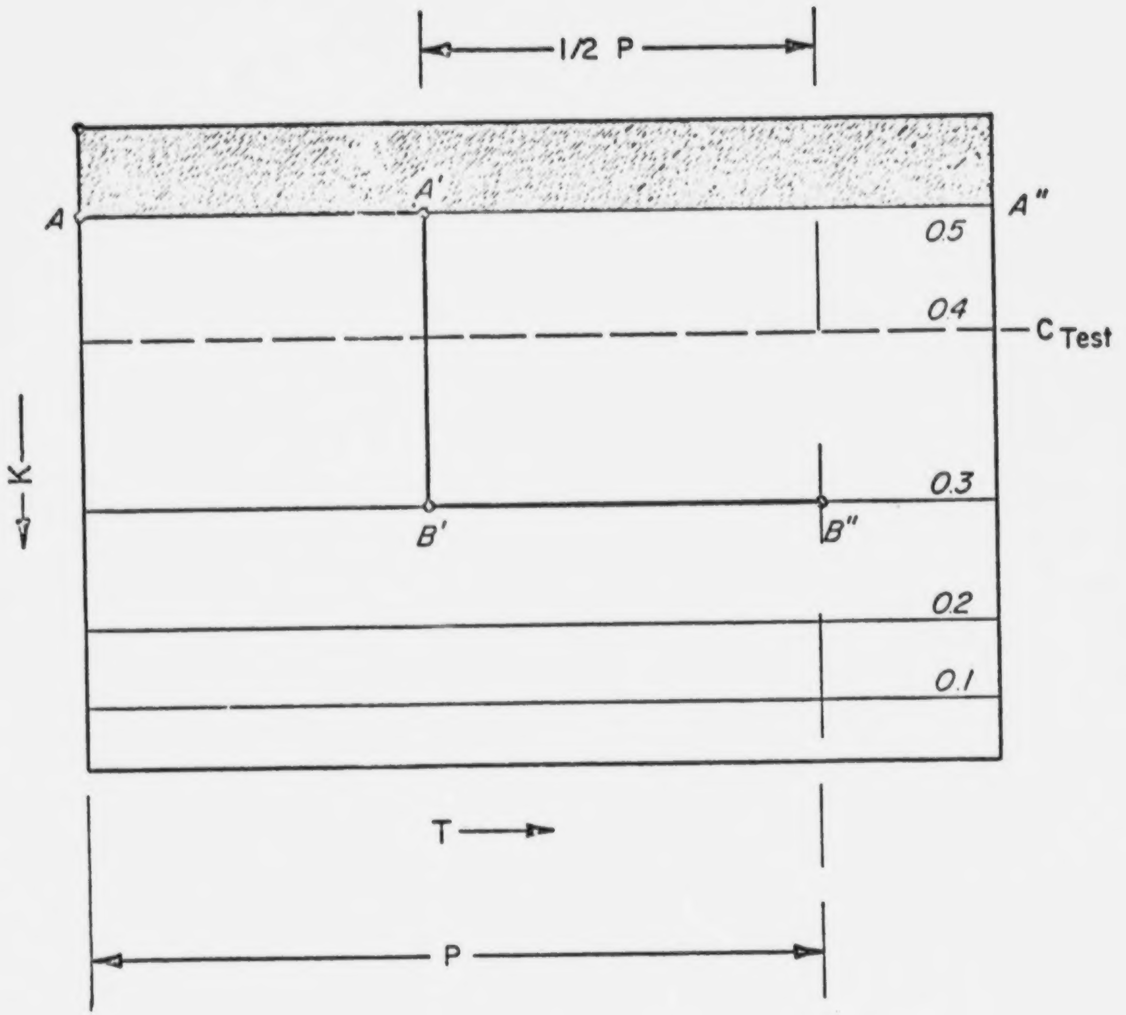

1/2 P
A
A'
A"
0.5
0.4
C Test
0.3
B'
B"
0.2
0.1
K
T
P

Figure A-7 Application of Averaging Criterion for Averaging Period P for a Single Receptor

7) The path which results from the above steps will meet all the criteria for averaging periods from 1 hour on up to the longest period considered.

A.3.3.2.2 Cutback Thresholds

The algorithm described above is driven by the control point threshold curve, which determines for any averaging period, the maximum predicted average concentration which will be allowed at any receptor before applying the next cutback step in the given switchmode strategy. Figure A-8 schematically shows three possible cutback threshold curves, labelled A, B, and C, which are designed to protect the 3-hour (0.5 ppm) and 24-hour (0.14 ppm) SO_2 standards. The actual curve used in the Kincaid program is given in Figure A-3. However a discussion of the general concept and objectives of threshold curves in general is useful for understanding the SCS more fully.

Each of the three curves of Figure A-8 contain a safety factor in that they all lie below the standards themselves. The difference in the curves lies in their degree of conservatism: Curve A is the most conservative since it cuts back at the lowest value for any averaging period, while curve C is the least conservative.

The trade-off between economic and air quality considerations is thus determined by the curve chosen: Curve A will be safer in SCS operation, but will result in higher plant cost due to more frequent cutback. Conversely, curve C will provide the least plant cost, but will provide a higher probability of exceeding standards.

A.3.3.2.3 Optimization of Control Action

An important consideration, as expressed in the fourth criterion of Section A.3.3.1 is the application of control measures during the time in which they will be most effective in reducing long term averaged concentrations, and not at other times. This requires that in anticipating the need for control, the cutback of plant emissions at some time

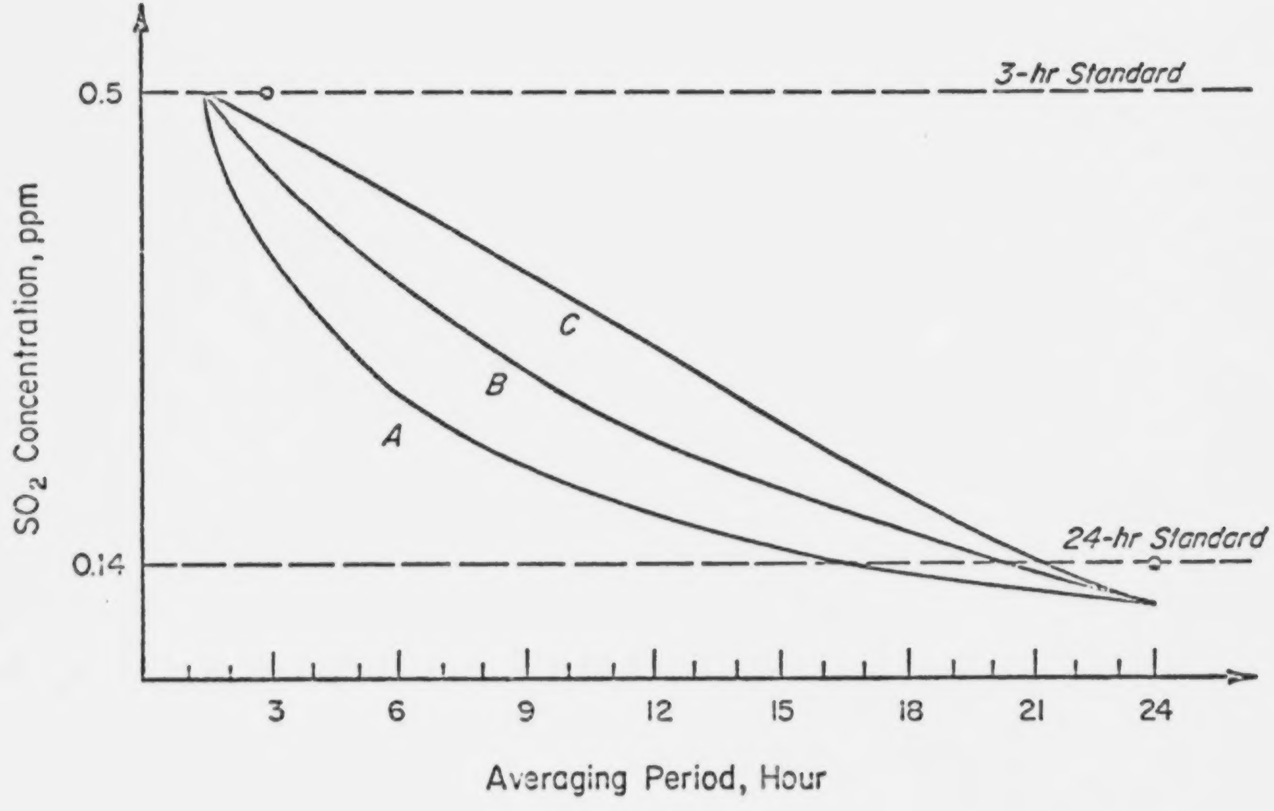


Figure A-8 Three Possible Control-Point Threshold Curves which Protect Both 3- and 24-Hour Standards, Ranging from Most Conservative (A) to Least Conservative (C) in the future should be carried out such that (1) long term averages are protected at all receptors; and (2) the minimum total cutback is obtained.

The first of these goals could be accomplished simply by reducing emissions - either immediately or at a time scheduled in the future - to a constant level such that all applicable long term averages would be protected for all receptors, and retaining this level for the remainder of the forecast period. This approach, although computationally simple, would result in periods of unnecessary load reduction and economic penalty.

The alternate approach, as implemented in the CONDEC model, provides for the maximum total generation by staging the cutback in successive steps, at all times keeping the operation path in the C-K-T space as close as possible to the forbidden or "plant inaccessible" region in that space. A simple example of the difference in the two approaches is shown in Figure A-9, in which an episode beginning at future time T_o is indicated by the shaded inaccessible region. In the simple approach, emissions are cutback at time T_o to a constant level for the remainder of the forecast period as indicated by path a'-a". In the optimum approach, each step in the cutback strategy is instituted for the time period necessary to avoid crossing into the forbidden region, as indicated by path b-b". The area between the two paths represents the total plant generation lost in using the former approach.

A.3.3.3 The Final Plant Operating Recommendations

The primary final result is the actual operating schedule for the forecast period. Other information is available to support and expand on this schedule. This includes the actual record of each cut made by CONDEC, the concentrations forecast by AQFOR, as well as the various average concentrations examined by CONDEC in its decision process.

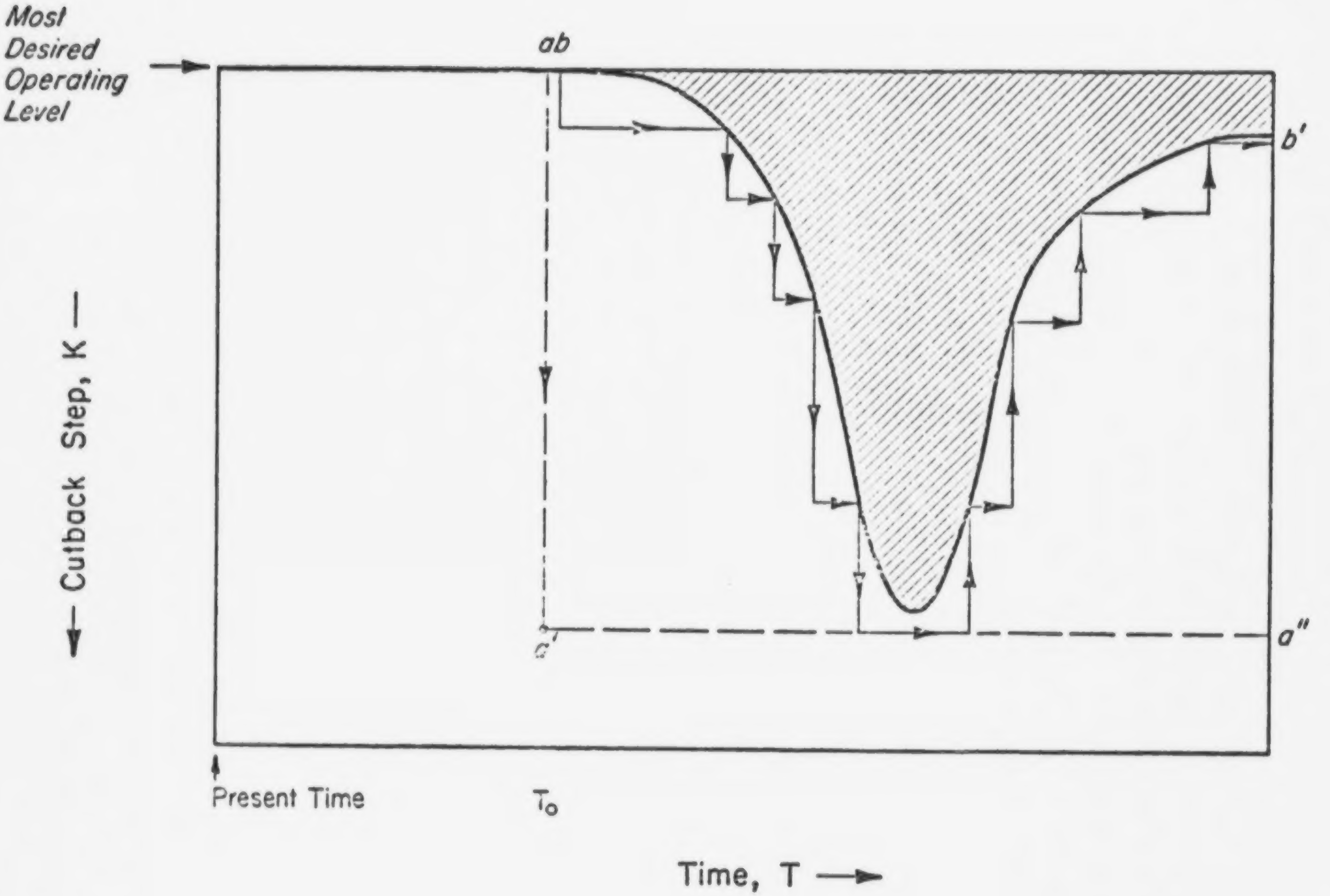


Figure A- 9 Comparison of Two Alternative Cutback Strategies: Curve a-a'-a" reduces emissions to a constant level at some future time T_o, while curve b-b' performs successive stages of cutback to optimize the total select operations

APPENDIX B

USER'S MANUAL FOR PROBL: THE RELIABILITY OF SCS METHODS PROGRAM

This appendix is a user's manual for the computer program PROBL, which was developed during the previous EPA Contract 68-02-1342 (1976). It is a relatively simple program, but to be used effectively it requires the preparation of considerable input data.

1.1 Description of Program Method

A frequency distribution is a representation of the fraction of the time a variable quantity assumes each of the possible values in its range. The frequency distribution of ground-level concentrations downwind of a source can be used in this program to provide information about the characteristics of the source emissions.

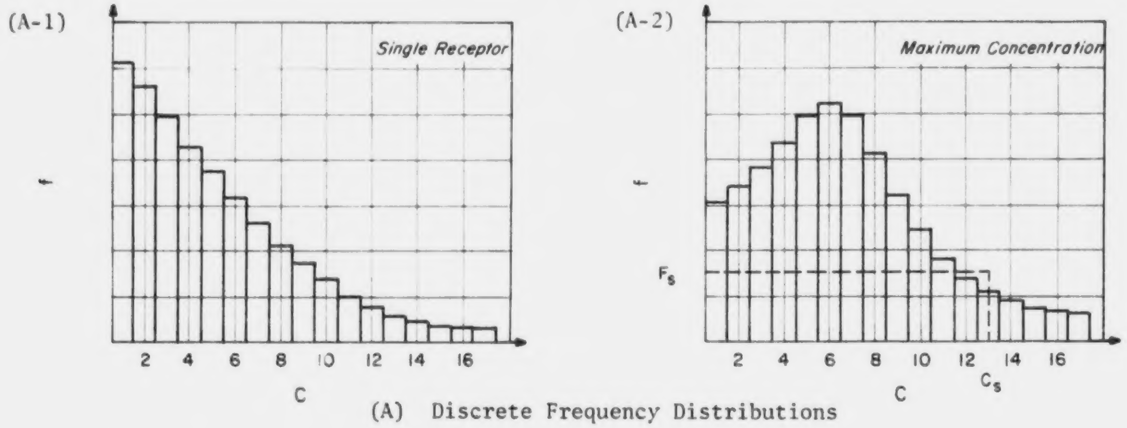
This subsection describes a model that analyzes the effectiveness of SCS operations in a probabalistic sense on the basis of the frequency distribution of contaminent concentrations. Figure 1-1A illustrates two typical concentration distributions. The first represents the frequency distribution of concentrations at a single receptor; the wind is often blowing in a direction other than from source to receptor, and hence concentrations are most frequently near zero. The second is representative of a distribution of the highest concentrations at any one of a network of receptors around a source. In the latter case, maximum concentrations near zero are less likely.

The value C_s has been designated on the abscissa of the maximum concentration graph to indicate the value of some air quality standard. The sum of the frequencies of occurrence of all concentration categories greater than C_s is the fraction of the time the air quality standard is expected to be exceeded. The value f_s on the ordinate of each graph has been designated to indicate the permissible frequency of concentration values exceeding C_s. To satisfy an air quality standard, the sum of the frequencies for values of concentration to the right of C_s must be less than f_s. Thus, from a compliance viewpoint, a more useful distribution is the cumulative frequency distribution associated with each of the frequency distributions discussed above. In this case, the sum of the frequencies of all values greater than the abscissa value is plotted as the ordinate. Figure 1-1B illustrates the cumulative frequency distributions associated with the distributions of Figure 1-1A. The sum over the frequency distribution of occurrence for concentrations greater than C_s can now be read directly from the ordinate of the graph.

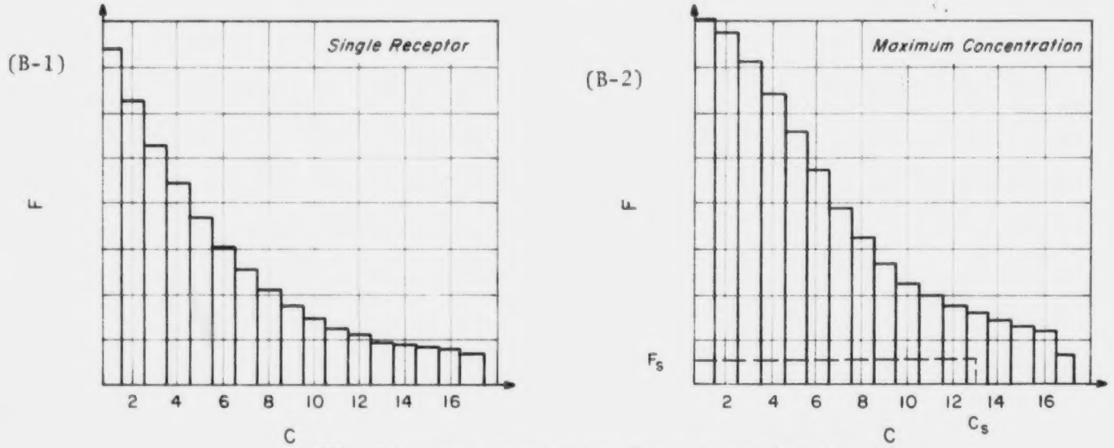
Since a continuous range of concentration values is possible, the step function presentation of the cumulative frequency distribution can be replaced by a smooth function as illustrated in Figure 1-1C. The goal of any control procedure directed toward compliance with an air quality standard is to reduce the locus of F at the abscissa value C_s below the dashed line representing F_s. When it is obvious which frequency distribution of the three presented in Figure 1-1 is being discussed, the term "distribution" will be used for convenience.

The cumulative frequency distribution can be used to illustrate the effects of any control procedure. Figure 1-2A represents a hypothetical distribution of maximum ground-level concentrations. Since the locus of F is above the dashed line at $C = C_s$, the source is in violation of standards. Assume the graph of F represents the uncontrolled conditions. Direct application of a constant emission control, which reduces plant impact uniformly by 50% (say, changing from 2% to 1% sulfur fuel or installing 50% efficient removal devices that operate continuously and do not affect plume rise), would move every value of F from the abscissa value C to the abscissa value C/2 to yield the graph illustrated in Figure 1-2B. The graph of F has been reduced, as required, below F_s to satisfy the air quality requirements. More generally and for the representation of any effective continuous emission control strategy, you could have moved every value of F from C to $\beta \cdot C$ where β is any value less than β_o such that $F(C_s/\beta_o) \leq F_s$. The resulting value of $F^*(C) = F(C/\beta)$.

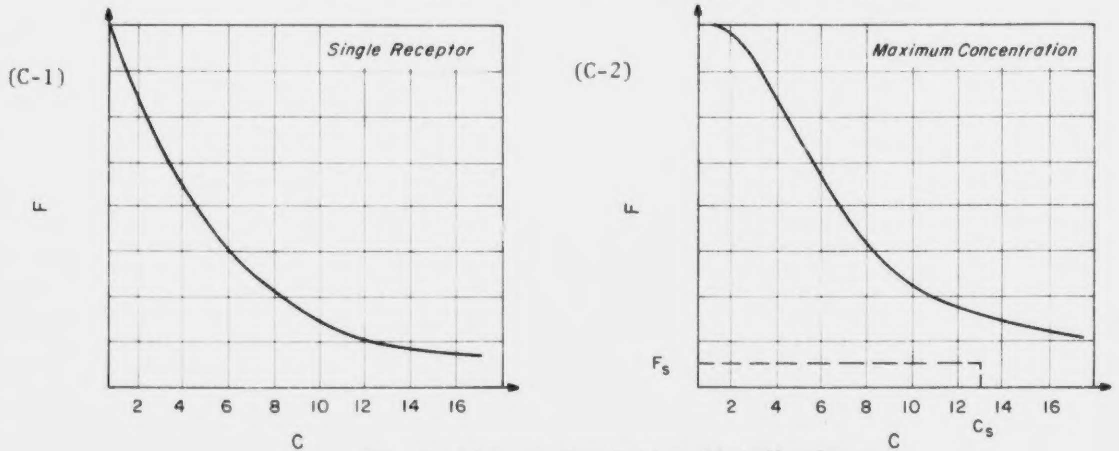
An alternative to a rigid emission control system such as discussed above is an SCS capable of changing the tail of the graph of F to reduce F^* to values below F_s for $C \leq C_s$. Figure 1-2C represents some emission reduction $\beta(C)$, which reduces emissions by exactly the amount required to achieve the standard all the time. In practice, no system will be so reliable. It is more likely that some fraction of the attempts to eliminate concentrations greater than C_s will be unsuccessful.



(A) Discrete Frequency Distributions



(B) Discrete Cumulative Frequency Distributions



(C) Continuous Cumulative Distributions

Figure 1-1 Representative Frequency Distributions for Ambient Concentrations from a Point Source. (Graphs A-1, B-1 and C-1 apply to a single receptor; Graphs A-2, B-2 and C-2 apply to the maximum concentrations from a network of receptors.)

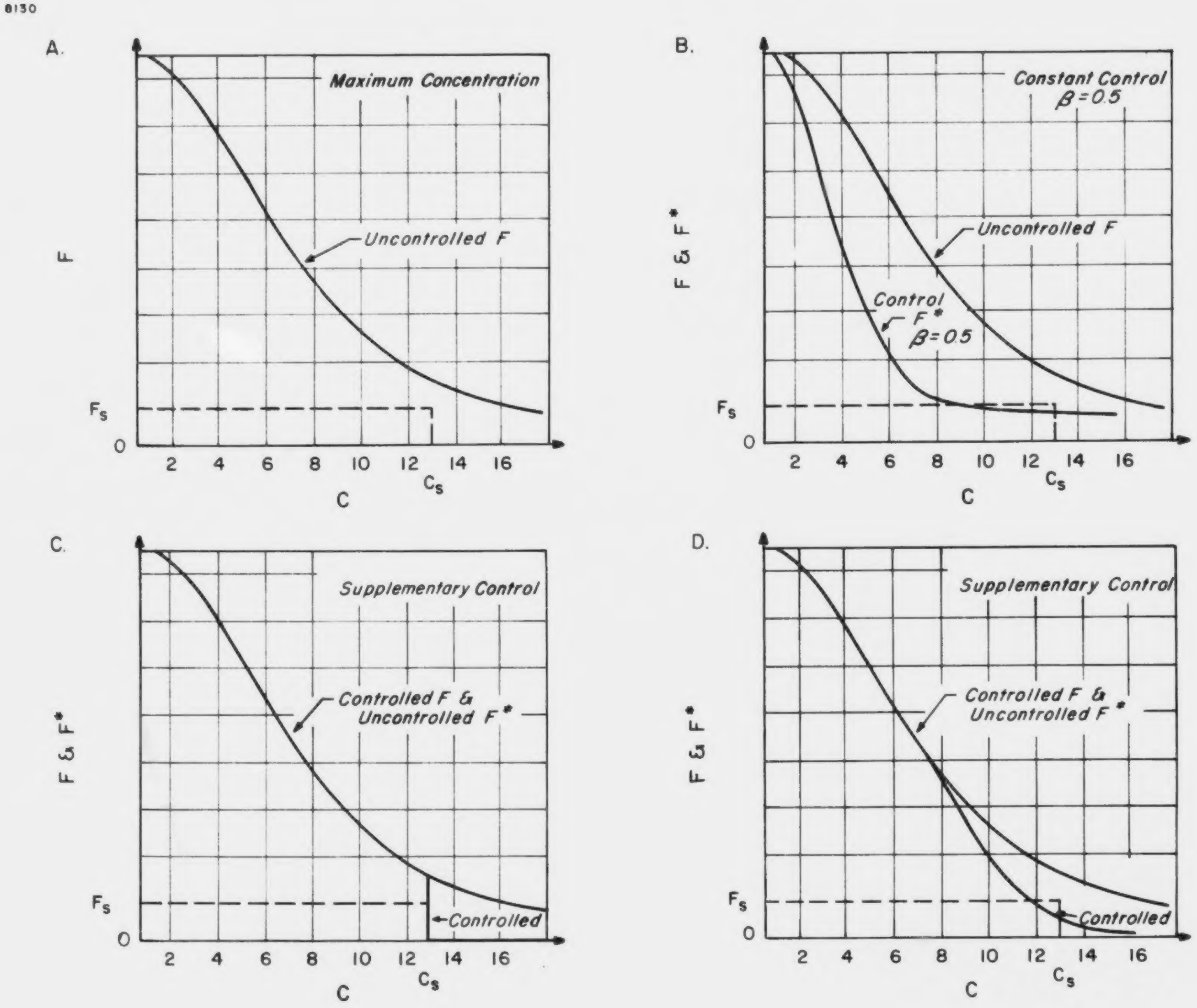


Figure 1-2 Representative Cumulative Frequency Distributions for Maximum Concentrations under Conditions of a) no emission controls, b) absolutely reliable constant emission controls, c) absolutely reliable supplementary emission controls, d) realistic supplementary emission controls.

Figure 1-2D represents a realistic frequency distribution resulting from the actual operation of an SCS. The curve of F* is not different from the curve of F at the low concentration end of the graph, in contrast to the constant emission reduction case of Figure 1-2B where concentrations must be well below standards before controls are reduced. The tail of the F* curve of Figure 1-2D is below the dashed line for values of $C > C_s$ as required. The values of $C > C_s$ would be the result of uncertainty (errors) in the operation of the SCS, but their frequency is so low that a reliable SCS is still maintained.

The ERT PROBL software package generates the frequency distribution of maximum ground-level concentrations due to the source under study with or without emission controls for analysis of the reliability of SCS methods. In particular, the program can generate the frequency distribution for a wide variety of possible SCS schemes.

The main assumptions of the analysis scheme are:

- a single source of SO_2 is responsible for observed concentration levels;
- without an SCS, emissions are independent of meteorological conditions;
- with an SCS, emissions are controlled according to rules that depend on predicted meteorological conditions and
- error in prediction (R_T) is independent of meteorological conditions.

Consider the following definitions relevant to understanding the model:

$c(x,t)$	is the concentration at time t and location x
$C(t)$	max $c(x,t)$; maximum concentration over all x locations at time t
$\underline{x}$	is the downwind location of $C(t)$
C_s	is the air quality standard or SCS threshold
$Q(t)$	is the emission rate without SCS

$M(t)$ is the meteorological function relating the maximum concentration $C(t)$ to source emission rate $Q(t)$; it includes the effects of stack height, wind conditions, mixing depths or any other pertinent meteorological inputs

R_T is the error ratio of concentration prediction defined as follows:

With or without an operating SCS, the observed maximum concentration C_o is related to the actual emission rate Q through the meteorological function M as follows:

$$C_o = Q \cdot M \text{ at time } t$$

With an operating SCS, the corresponding maximum predicted concentration is related to the actual emission rate Q and the meteorological function M (defined above) through the Error Ratio R as follows:

$$C_p = Q \cdot M \cdot R \text{ at time } t$$

From the above, the error ratio can be defined as

$$R_T = C_p/C_o$$

The observed maximum concentration under SCS control is given by $C_c = Q_c \cdot M$, where Q_c is the SCS controlled emission rate determined from the forecast concentration C_p.

The value of Q_c depends on the SCS control strategy being used. Two examples of possible control strategies are:

1) Fuel Switching

$$Q_c = \begin{cases} Q & \text{if } C_p \leq \gamma \\ \beta Q & \text{if } C_p > \gamma \end{cases} \qquad \text{(Strategy 1)}$$

where β is a constant (less than one) that depends on the nature of the fuels. A switch from 2% sulfur fuel to 0.5% sulfur fuel means $\beta = 0.25$. The threshold parameter γ is a function of the air quality levels attempted to be maintained.

2) Process Curtailment

$$Q_c = \begin{cases} Q & \text{if } C_p \leq \gamma \\ \gamma/C_p \cdot Q & \text{if } C_p > \gamma \end{cases} \qquad \text{(Strategy 2)}$$

In general, the threshold γ is set below standards to provide a margin of safety.

The functions Q, M and R require more careful description. Q(t) can be a well-defined quantity if emission monitors are used. Alternately emission rate is related simply to the production rate, or to the load of the plant under study. If the plant emissions are not monitored, some engineering estimates of the frequency distribution of Q can often be made from production or process control information.

The function M(t) can be determined in various ways. For an operation with an extended historical air quality monitoring record, M(t) could be estimated from the ratios of measured maximum concentrations $C_o(t)$ and known emission rates Q(t). Where a shorter monitoring record exists with an extended meteorological data bank, M could be the output of a statistical model; for example, $M = a_1m_1 + a_2m_2 + \text{--} + a_nm_n$ where m_1, m_2, --- m_n are meteorological parameters, such as stability or air mass characteristics, and a_1, a_2, --- a_n are regression coefficients determined from the available air quality data. If the distributions of the m_1s are known, the statistical data of the shorter monitoring period can be combined with the longer period meteorological distributions, as is frequently the case since meteorological data have been collected at many locations by the National Weather Service for periods as long as a century. Finally, where little site monitoring data exist, outputs from Gaussian diffusion or other air pollution models can be used in conjunction with the meteorological data to construct M.

An alternative method is available for circumstances when measured concentration data are not available. The function M can be approximated with a predicted ground-level concentration divided by the emission rate. As is the case with the other concentration distribution, it must be divided by Q to obtain M. The predicted maximum ground-level concentration can be obtained from any reliable model appropriate to the site. The subroutine METCLASS requires the predicted M value as a function of user-specified wind speed, wind direction and stability classes. The subroutine METDS then requires a frequency of occurrence of each class set up in METCLASS. Any available joint frequency distribution can be used for this purpose once a model evaluation for each class is obtained. Use of the predicted concentrations to develop M eliminates the need for measured concentrations to be entered in the CLASS and DENSITY subroutines.

The function R_T may be determined from historical real-time monitoring and forecasting data. Since the function R_T will depend on the unique forecasting difficulties for each SCS scheme, initial estimates of R_T must be evaluated during the design and initial testing of the SCS. The upgrading of an SCS as time proceeds will involve periodic reevaluations of this function.

Given the functions $Q(t)$, $M(t)$ and R_T over an appropriate averaging time period, frequency of occurrence distributions can be readily derived for the various magnitudes of the observed or determined values of Q, M and R_T. Thus, the time history data are transformed into a frequency of occurrence distribution. For purposes of future estimations, the frequency of occurrence distributions become expected probability density functions.

When the frequency distributions are determined, for Q, M and R_T, as defined above, the analysis scheme will be capable of generating the following basic information:

1) the number of violations to be expected without and with any SCS scheme;

2) the percentage of production lost if the SCS scheme is a load reduction program;

3) the percentage use of high-and low-sulfur fuel in a fuel switching SCS program and

4) the dependence of the number of violations, production lost and/or percentage use of high-and low-sulfur fuel on the implementation threshold (γ), model calibration, meteorological forecasting skill and/or the difference in sulfur content of the two switching fuels.

The exact mathematical reasoning leading to the previous conclusions can be shown. P_X is defined as the probability density function for the variable X. Then, the probability of the variable X having a value between a and b is

$$F_X = \int_a^b P_X(\zeta)\, d\zeta$$

Assume that there exist probability density functions for M and Q, and you wish to generate a frequency distribution for C when no SCS is operating. If A is any concentration value, ε is a variable and Q and M are independent of each other and random variables; then

$$\begin{aligned} P_C(C = A) \;=\; & P_Q\,(Q = \varepsilon) \cdot P_M\,(M = A/\varepsilon) + \\ & P_Q\,(Q = 2\varepsilon) \cdot P_M\,(M = A/2\varepsilon) +\text{---} \\ & + P_Q\,(Q = n\varepsilon) \cdot P_M\,(M = A/n\varepsilon) +\text{---} \end{aligned}$$

or, in the limit as $\Delta\varepsilon$ approaches 0

$$P\,(C = A) = \int_0^\infty P_Q\,(Q = \zeta) \cdot P_M\,(M = A/\zeta)\, d\zeta$$

or

$$P_C\,(A) = \int_0^\infty P_Q(\zeta) \cdot P_M\,(A/\zeta)\, d\zeta$$

Expressing the operator above by *,

$$P_C = P_M * P_Q$$

This equation states that the probability density function for maximum ground-level concentrations can be derived from the convolution of the probability density functions for M and Q. Therefore, the frequency distribution of ground-level concentrations for an uncontrolled plant can be deduced from determinations of M and Q.

Once P_C is known, the graphs corresponding to Figure 1-1B can be displayed, and the probability of violating standards is directly known.

Next, consider case when the SCS is operating. In this case, $C_c = Q_c \cdot M$, where subscript c denotes the functional value when the SCS is operating. Q_c is no longer independent of meteorology since the operation of the SCS depends on meteorological forecasting.

P_Q will, therefore, also be generally dependent on P_M and will vary for different control strategies. For computer solutions to the convolution integration, the dependence of these quantities on each other can be readily simulated.

Assuming that the error ratio R_T is independent of M and of Q and given P_R, P_M and P_Q, it is possible to use the control strategy rules for determining Q_c to numerically evaluate P_{Cc} under the SCS control.

In this case $C_p = M \cdot Q \cdot R$. The value of Q_c is determined in each case from the predicted value of concentration C_p and from the strategy (for example, Strategy 1 or 2). From the resulting distribution of Q_c, the value of P_{Cc} is obtained from the equation

$$P_{Cc} = P_{Qc} * P_M$$

Note the parallel nature of this equation and the equation for P_C.

Thus, the existing frequency distribution of ground-level concentrations for a plant can be determined from archived measurements of Q and M and from records of air quality forecasting accuracy during operational use of the SCS to determine R.

P_C is determined by assuming the values of Q and M are quantified so they can assume only a finite number of values. Therefore, P_Q and P_M represent probabilities rather than probability densities. The integral is then replaced by a numerical scheme, which is solved on a digital computer. Similarly, for the generation of P_{Cc}, the function R is assumed to be quantified and the probabilities of the quantified values of P_{Cc} are determined numerically. The numerical scheme employed by the ERT computer program to generate the above described frequency distributions can be modified to allow interdependence of Q and M. This property of the program is particularly valuable for operations where changes in effluent SO_2 emission rates may be associated with large changes in plume rise.

A single hypothetical example of the convolution technique used in PROBL may help to demonstrate the program's function. The values presented here are conjectural and only serve as a sample problem. If Q, the emission rate, is held constant at 1,300 grams per second, sample ranges of values of the error ratio R and the meteorological function M (in 10^6 sec/m^3) are given below:

R_T	M (10^6 sec/m^3)
2.0	2.0
1.5	1.0
1.5	1.0
1.5	0.5
1.0	0.5
1.0	0.2
0.5	0.2
0.5	0.1
0.5	0.1
0.2	0.1

These are the values for 10 samples. Values of $M > 1$ (concentration greater than 1,300 $\mu g/m^3$, e.g., the standard) when multiplied by the small values of R_T would result in combinations exceeding the standard. The last four R_T values fall into that category. That presupposes that for all times when M is 2.0 and R_T is greater than 0.5, the SCS calls a control action.

To ascertain the percentage of time that control actions would be called and the severity of the reductions, PROBL is used to obtain the convoluted probability summarized in Table 1-1. The values of predicted concentration in Table 1-1 are produced when the sets of R_T and M are multiplied together, and the distribution of values is indicated by the number of events. When the value of predicted concentration is equal to 1.0, the standard is maintained and no control requirement is necessary. Thus, for values of predicted concentrations less than 1.0, the ratio Q/Q_o represents an increase in emissions that could be allowable to attain the standard. However, when predicted concentrations are greater than 1.0, the ratio Q/Q_o shows the reduction in emissions needed to reach standards (e.g., predicted concentration = 3.0 or factor of 3 greater than standard, then emissions must be reduced by 1/3 or 0.33). Thus, for these cases, reduction in production is required, and the frequency is calculated by multiplying the number of events for those cases with Q/Q_o. This table indicates that a total of 14% of the time (number of events for four highest predicted concentrations) some reduction from rated capacity would be required. When combined with the implied reductions from rated capacity, the actual percentage of rated capacity that the plant would produce is 93.25% (86% for cases equal to or less than standard plus 7.25% for the cases that require a reduction from rated capacity.

If the model or methods were altered so that the R_T values are doubled, the result would be only one possible combination that would exceed the standard but there would be a generation penalty in that the percentage capacity would fall to 83.125%.

The original study (EPA 1976a) provides a set of example cases of the use of PROBL that may help the reader understand the sensitivity analysis with β and γ that can be performed. These examples are presented in Appendix C.

1.2 Program Description

The program PROBL is arranged as shown in Figure 1-3. The main program simply calls subroutines directed by the cards submitted by the user and interpreted by the subroutine INPUT. There is some initial data required by the subroutine INPUT, which is entered through a namelist INPUT. Those required data are the number of increments you will use to specify the probability of occurrence of emissions (Q), meteorology (M) and SCS error ratio (R). These increments are called classes

TABLE 1-1

SAMPLE DEMONSTRATION OF PROBL CALCULATIONS

Value of Predicted Concentration	Number of Events	Q/Q_o* Implied to meet $C < 1300$	Percentage of Capacity
4.0	1	0.25	0.25
3.0	3	0.33	1.00
2.0	4	0.50	2.00
1.5	6	0.67	4.00
1.0	9	1.00	9.00
0.75	6	1.33	6.00
0.50	10	2.00	10.00
0.40	3	2.50	3.00
0.30	6	3.33	6.00
0.25	6	4.0	6.00
0.20	9	5.0	9.00
0.15	9	6.67	9.00
0.10	14	10.0	14.00
0.05	9	20.0	9.00
0.04	2	25.0	2.00
0.02	3	50.0	3.00
	100		93.25%

* Q_o = 1300 grams/second

804487 or
804437

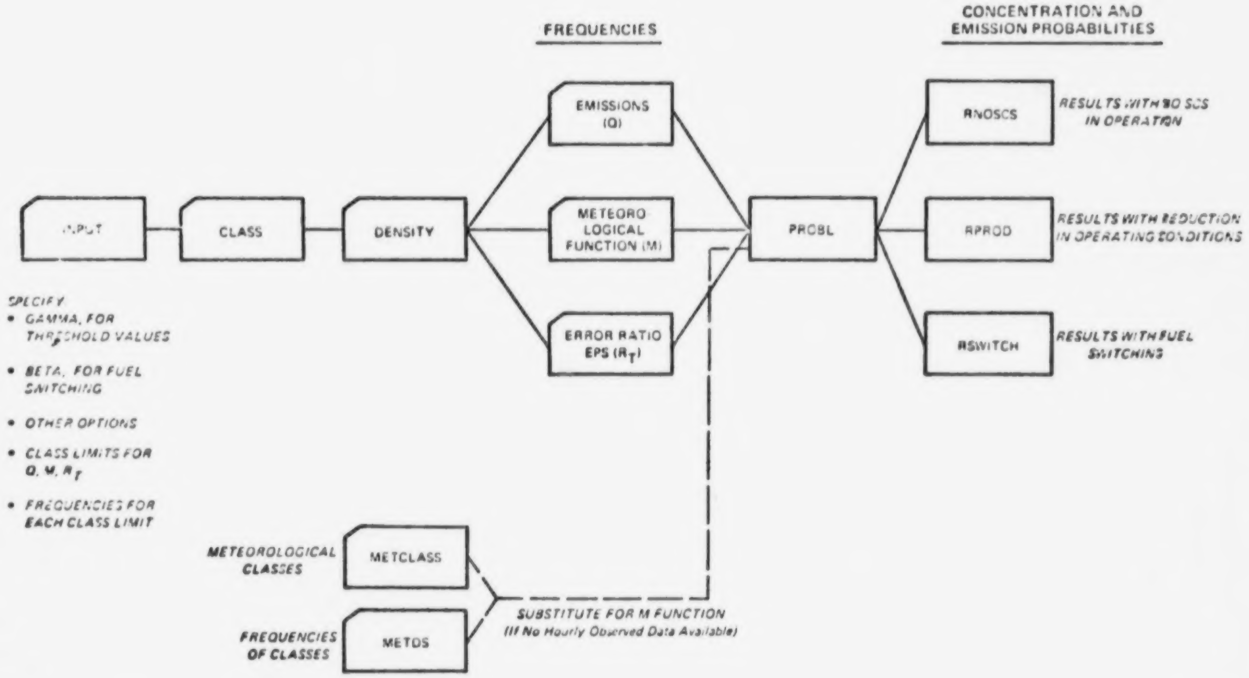

FREQUENCIES
CONCENTRATION AND EMISSION PROBABILITIES
INPUT
CLASS
DENSITY
EMISSIONS (Q)
METEORO LOGICAL FUNCTION (M)
ERROR RATIO EPS (R_T)
PROBL
RNOSCS
RESULTS WITH NO SCS IN OPERATION
RPROD
RESULTS WITH REDUCTION IN OPERATING CONDITIONS
RSWITCH
RESULTS WITH FUEL SWITCHING
SPECIFY
• GAMMA, FOR THRESHOLD VALUES
• BETA, FOR FUEL SWITCHING
• OTHER OPTIONS
• CLASS LIMITS FOR Q, M, R_T
• FREQUENCIES FOR EACH CLASS LIMIT
METEOROLOGICAL CLASSES
METCLASS
FREQUENCIES OF CLASSES
METDS
SUBSTITUTE FOR M FUNCTION
(If No Hourly Observed Data Available)

Figure 1-3 Summary Flow Diagram: PROBL Computer Program

in the program and a equivalent number of classes can be entered for each of the three variables. In addition, you must specify:

1) the threshold value (GAMMA), in ppm or $\mu g/m^3$, above which the SCS calls for either a switch in fuels or reduction in load;

2) a fuel switching ratio (BETA) that gives the ratio of percentage sulfur content in the fuel for a fuel switching SCS and

3) the last increment (HINORM) for the M distribution to be used.

The INPUT namelist is then followed by cards that specify the subroutines to be used. Two subroutines are essential to the program because they process the remainder of the data required for the evaluation. The subroutines are CLASS and DENSITY. In subroutine CLASS, the increments are specified for each of the three variables: (1) error ratios, referred to as EPS, (2) the meteorological probability function, referred to as CONC since most often it is given as a distribution of ground-level concentrations and (3) the emissions Q. The subroutine DENSITY then requires the specification of the probability, percentage occurance expected, for each of the increments entered in CLASS. You, therefore, need to provide the probabilities of each of these functions and the program merely convolutes them into an expected frequency distribution of maximum ground-level concentrations, in ppm or $\mu g/m^3$.

If the meteorological function cannot be defined by observed data, predicted results or concentrations that are associated with the joint occurrence of wind direction, wind speed and stability can be used. This function can be directed through the subroutines METCLASS and METDS.

The data input deck must be preceeded by a card PARAMETER, which initiates the program and the last card must be an ENDJOB, which terminates the program.

The other subroutines can be called as needed and produce the following outputs.

- RNOSCS - The subroutine this key word calls generates a table of the frequency distributions of emissions and concentrations when no SCS is used. Therefore the emissions are independent of meteorological conditions.

- RPROD - The subroutine this key word calls generates a table of frequency distributions of emissions and concentrations when the load of the plant is reduced for all predicted concentrations above the threshold (GAMMA).
- RSWITCH - The subroutine this key word calls generates a table of frequency distributions of emissions and concentrations when the fuel type is switched by the ratio on BETA for all predicted concentrations above the threshold (GAMMA).

There are six ERT standard subroutines called in the program that perform primarily input and output functions. They are HEADR, INPUT, TXLOC, ERRX, TABLE and INE. Descriptions of the Job Control Language (JCL) and each keyword that initializes subroutines in the program are presented in the following section.

1.2.1 Control Language and Data Deck Setup

Control Language Requirements

The following IBM JCL is required to link-edit and execute the PROBL program on an IBM System/360 Operating System:

```
// Jobname (Job identification, accounting information),

// MSGLEVEL=1, CLASS=B, TIME=1

// R EXEC FORTHLG, REGION.GO=150K, TIME.GO=1

// LKED.PROB DD DSN=XXXX.PROBL, DISP=SHR

// LKED.ERT DD DISP=SHR, DSN=YYYY.(Library file)

// LKED.SYSLIN DD*
      INCLUDE PROB (MAIN, BLOCK, COMP, INPARM, METD, METCLA)
      INCLUDE PROB (CLASS, DENSIT, RSWITC, RPROD, TABLR, RNOSCS)
      INCLUDE ERT (HEADR, INE, ERRX, INPUT, TABLE, TXLOC)
      ENTRY MAIN

// GO.FT09F001 DD DSNAME=YYYY.LOGDATA, DISP=SHR

// GO.F06F001 DD SYSOUT=A

// GO.FT05F001 DD*
```

```
(card input deck)

/*
```

where:

Job name = user specified job name

(Job identification, accounting information) = job accounting information, system dependent

XXXX = volume serial name containing program

YYYY = data set number for identification

(Library file) = File containing subroutines such as HEADR, INE, etc.

(card input deck) = cards containing parameter file and probability distributions for R_T, meteorological and emission functions

This example assumed that the PROBL program has been compiled on the system.

Data Deck Setup

The data card deck required for input to the program must be set up as follows:

- parameters and input,
- class descriptions for Q, M and R,
- density functions or, more accurately, probabilities for Q, M, R and
- initialization cards for determining concentration and emissions probabilities produced without SCS, with load reduction, and fuel switching strategy.

The input to PROBL is directed through the use of keywords, which initiate program functions. There are currently nine keywords in PROBL. They are PARAMETERS, CLASS, DENSITY, RNOSCS, RPROD, RSWITCH, METCLASS, METDS and ENDJOB. Each is discussed separately.

PARAMETERS

The keyword PARAMETERS is used to set program options. The input to this keyword is in the following format:

CARD 1 - consists only of the word PARAMETERS punched in columns 1-10.

CARD 2 - consists only of the words &INPUT punched in columns 2-7.

CARD 3-N - must contain the variables in columns 2-80. These variables, described in Table 1-2, must be specified by the user since there are no default values. Each is defined by means of an equal sign, such as NC=20, for 20 meteorological function classes.

LAST CARD - contains only &END punched in columns 2-5.

CLASS

The keyword CLASS is used to define the lower class limits for ranges of values for three probability sets: Q, R (described as EPS), and concentrations (CONC). The format and meaning of the variables used in this keyword is presented in Table 1-3 with a general description described as follows:

CARD 1 - contains the word CLASS punched in columns 1-5.

CARD 2 - contains the letter Q in column 1. This introduces the cards for the class intervals used for the emissions (first set of data).

CARDS 3-N - contain the lower class limits for different values of Q, with, at the most, six values per card. Each value is allowed ten columns starting in column 11.

CARD N+1 - contains the data delimiter, 88888, punched in columns 1-5.

FOLLOWING CARDS - repeat the same format as cards 2 through N+1, only the information for Q is replaced with values for EPS for the second set of data and concentrations for the third set. As seen from Table 1-3, EPS and CONC have replaced the letter Q on CARD 2 when describing the limits for R and concentrations, respectively.

TABLE 1-2
LIST OF PARAMETER VARIABLES

Name	Type	Meaning
NC	Integer	Number of the meteorological function classes (must be less than 500)
NE	Integer	Number of error classes (must be less than 500)
NQ	Integer	Number of emission classes (must be less than 500)
GAMMA	Real	Switch threshold (in ppm or $\mu g/m^3$)
BETA	Real	Ratio of the percent sulfur content of the low sulfur content fuel to the percent sulfur of the high sulfur content fuel (i.e., the fuels used in fuel switching $\beta \leq 1$)
HINORM	Real	The increment of the last meteorological function category (in ppm or $\mu g/m^3$)
		(Note: Parameters are punched in columns 2-80 and define values by an equal sign, "=")

TABLE 1-3

DESCRIPTION OF CLASS CARDS

Class Limit Sets	Card Groups	Name	Number of Cards	Columns (Format)	Meaning
1	1	Q	1	Column 1 (A1)	Emission classes
	2	Data Cards	NQ/6	(A4,6X,6G10.5)	$Q = \frac{\text{Actual Mw Capacity}}{\text{Total Mw Capacity}}$
				Columns 11-20	First lower class limit
				21-30	Second lower class limit
				. . .	. . .
				61-70	Sixth lower class limit
	3	88888	1	Columns 1-5 (A5)	Data delimiter
2	4	EPS	1	Columns 1-3 (A3)	Error ratio classes
	5	DATA	NE/6	(A4,6X,6G10.5)	$\mathrm{EPS} = R_T \frac{C_p}{C_o}$ where: C_p = predicted concentration C_o = observed concentration
				Columns 11-20	First lower limit
				21-30	Second lower limit
				. . .	. . .
				61-70	Sixth lower limit
	6	88888	1	Columns 1-5 (A5)	Data delimiter
3	7	CONC	1	Columns 1-4 (A4)	Meteorological function classes
	8	DATA	NC/6	(A4,6X,6G10.5)	Observed Concentrations Co or values of Co/Q
				Columns 11-20	First lower limit
				21-30	Second lower limit
				. . .	. . .
				61-70	Sixth lower limit
	9	88888	1	Columns 1-5 (A5)	Data delimiter
	10	99999	1	Columns 1-5 (A5)	Subroutine delimiter

LAST CARD - contains the subroutine delimiter 99999 in columns 1-5.

DENSITY

The keyword DENSITY calls for the subroutine which describes the probabilities for each class defined in the CLASS keyword for three sets of data; Q, EPS, and meteorology (MET). The format and meaning of the variables used in this keyword are presented in Table 1-4 with a general description as follows:

CARD 1 - contains the word DENSITY punched in columns 1-6.

CARD 2 - contains the letter Q in column 1. This introduces the frequencies for the emissions punched on the following cards.

CARDS 3-N - contain the frequencies of emissions appropriate for the class intervals described in the keyword CLASS. At most, there are six values allowed per card with each value specified in increments of ten columns starting in column 11.

CARD N+1 - contains the data delimiter, 88888, punched in columns 1-5.

FOLLOWING CARDS - repeat the format as cards 2 through N+1, only the information for Q is replaced with values for EPS, the second set of data, and Meteorology, the third set. As seen from Table 1-4, EPS and MET have replaced the letter Q on CARD 2 when describing the frequencies for EPS and meteorology, respectively.

LAST CARD - contains the subroutine delimiter, 99999, in columns 1-5.

METCLASS

This keyword requires the entry of data for each meteorological class to be used if predicted M functions are to be substituted for measured M functions. The M function can be assigned values from the results of model predictions derived for 480 weather conditions (6 wind speed classes by 16 wind direction classes by 5 stability classes). These meteorological conditions which correspond to a particular M function class are grouped together to define that class. The M function class limits are those described in the CLASS subroutine for CONC.

TABLE 1-4

DESCRIPTION OF DENSITY CARDS

Probability Sets	Card Groups	Number of Cards	Name	Columns (Format)	Meaning
1	1	1	Q	Column 1 (A1)	Emission probabilities
	2	NQ/6	Data	(10x,6G10.5)	$\frac{\text{\#hr Q for each class}}{\text{total hours}}$
				Columns 11-20	value for first class
				Columns 21-30	value for second class
				.	.
				.	.
				.	.
				Columns 61-70	value for sixth class
	3	1	88888	Columns 1-5 (A5)	data delimiter
2	4	1	EPS	Columns 1-3 (A3)	error ratio probabilities
	5	NE/6	Data	(10x,6G10.5)	$\frac{\text{\#hr EPS for each class}}{\text{total hours}}$
				Columns 11-20	value for first class
				Columns 21-30	value for second class
				.	.
				.	.
				.	.
				Columns 61-70	value for sixth class
	6	1	88888	Columns 1-5 (A5)	data delimiter
3	7	1	MET	Columns 1-3 (A3)	meteorological function probabilities
	8	NC/6	Data	(10x,6G10.5)	$\frac{\text{\# CONC for each class}}{\text{total hours}}$
				Columns 11-20	value for first class
				Columns 21-30	value for second class
				.	.
				.	.
				.	.
				Columns 61-70	value for sixth class
	9	1	88888	Columns 1-5 (A5)	data delimiter
	10	1	99999	Columns 1-5 (A5)	package delimiter

The format and meaning of the variables used in this keyword are presented in Table 1-5 with a general description as follows:

CARD 1 - contains the word METCLASS in columns 1-8.

CARD 2 - contains the word CLAS in columns 1-4 and the sequence of the meteorological function class in columns 11-20. (For example, the first class is 1, second is 2, etc.)

CARDS 3-N - contain the appropriate meteorological categories for the first M function. There are six groups of meteorological categories allowed per card with 10 columns for each category starting in column 11. The general format is as follows:

Columns	Parameters
	First meteorological category:
11-12	Wind Speed class (1-6)
14-16	Wind direction class (1-16)
18-19	Stability (1-5)
	Second meteorological category:
21-22	Wind speed class
24-26	Wind direction class
28-29	Stability

Four additional categories can be inserted, if necessary, following the same format.

CARD N+1 - contains the data delimiter, 88888, in columns 1-5.

Each additional M function class follows the same format from CARD 2 through N+1 until the entire M function has been defined.

LAST CARD - has the subroutine delimiter, 99999, in columns 1-5.

TABLE 1-5

DESCRIPTION OF METCLASS CARDS

Cards Groups	Name	Number of Cards	Columns (Format)	Meaning
1	METCLASS	1	Colums 1-8 (A8)	Meteorological function classes
2	CLAS	1	Columns 1-4 (A4)	The meteorological function class defines the meteorological categories (following cards) which are represented by the class. The first class is numbered 1, with each successive class numbered 2 through last class limit
	Sequence of meteorological function classes, starting with 1		Columns 11-20 (I10)	
3	Data Cards	M/6	[A4,6X,6(I2,1X,I3,I2,1X)]	Applicable meteorological categories for first M function
			Columns 11-12	Wind speed class (1-6)
			Columns 14-16	Wind direction class (1-16)
			Columns 18-19	Stability (1-5)
				Six groups of meteorological categories may be specified for each card.
				M represents the number of cards for which there are meteorological categories for first M function
4	88888	1	Columns 1-5 (A5)	Data delimiter
N	[Card groups 2-4 are repeated for the successive M function classes and the respective meteorological categories. The total number of M function classes are those described in the subroutine class.]			
N+1	99999	1	Columns 1-5 (A5)	Subroutine delimiter

METDS

The keyword METDS calls the subroutine that describes the frequency of the meteorological situations specified by the classes and values in METCLASS. The format and meaning of the variables are shown in Table 1-6 with the following general description.

CARD 1 - contains the word METDS in columns 1-5

CARDS 2-N - contain the word METD in columns 1-4 followed by the meteorological category and frequency. The categories are defined as wind direction, 1-16, and stability, 1-5, while the order of the frequencies defines the six wind speed classes. The general format is:

Columns	Parameter
1-4	METD (This is included only on the first card.)
6-7	Wind direction class (1-16)
8-10	Stability class (1-5)
11-20	First wind speed class frequency associated with the wind direction and stability classes
21-30	Second wind speed class frequency
.	.
.	.
.	.
61-70	Sixth wind speed class frequency

This format is repeated for each category. Since there are 16 wind direction classes and 5 stability classes (with six wind speed classes included for any combination of the two), there are potentially 80 cards needed as input for this subroutine.

LAST CARD - includes the subroutine delimiter, 99999, punched in columns 1-5.

TABLE 1-6

DESCRIPTION OF METDS CARDS

Card Groups	Name	Number of Cards	Column (Format)	Meaning
1	METDS	1	Columns 1-5 (A5)	Meteorological frequency subroutine
2	Data Cards	N	(A4,1X,I2,I3,6G10.5)	Meteorological categories and frequencies:
	METD	-	Columns 1-4	Introduces data cards
	Meteorological Categories	-	6-7	Wind direction class (1-16)
			8-10	Stability class (1-5)
	Frequencies	-	11-20	First wind speed class frequency
			21-30	Second wind speed class frequency
			. . .	. . .
			61-70	Sixth wind speed class frequency
				This second card group is repeated until all meteorological categories have been defined by the associated frequencies.
3	99999	1	Columns 1-5 (A5)	Subroutine delimiter

RNOSCS, RPROD, RSWITCH

These keywords initiate the subroutines described earlier. Each keyword requires only one card with the keyword punched in columns 1-7. The output produces a listing, by classes, of the probabilities of concentrations and emissions for the subroutine specified.

ENDJOB

This keyword causes the program to end. There is only one card with the word ENDJOB punched in columns 1-6.

1.2.2 Diagnostic Messages

Fatal error messages are printed when an error is detected that causes the program to stop execution. This is normally due to an error with some input data. The following is a list of the possible fatal error messages for the subroutines and the corrective action that should be taken.

Subroutine	Error Number	Problem	Corrective Action
INPARM	800	Not all inputs are present in the parameters package	Check for missing value; NC, NQ, NE, BETA, GAMMA, HINORM
DENSITY	100	More density values were input than were specified in CLASS	Correct the number of frequencies input
CLASS	100	More class values were input than were specified in parameters	Check the values for NC, NQ, NE
	250	Data card is incorrectly punched with keyword	Change card that has keyword in wrong location
METCLASS	10	Keyword not included	Check for keyword CLAS
INPUT	80	Error in input packages	Correct for missing input packages

1.2.3 PROBL Example

Figure 1-4 shows an example of complete input of PROBL including the JCL, parameters package, and frequencies for Q, MET, and EPS that were used in Section 5.0 for the one unit case. In this case, neither METCLASS nor METDS is used since the M function has been defined using observed concentrations. In the parameters package, there are 20 classes of emissions (NQ=20), concentrations (NC=20), and error ratios (NE=20). Also, the threshold value is equal to 0.385 (GAMMA=0.385) with a fuel switching ratio of 1.0 (BETA=1.0). A value of 1.0 for BETA means that there will be no reduction in percent sulfur in the fuel although concentrations may be above the threshold. The last increment of the M function is set to 0.03 (HINORM=0.03). The class limits (CLASS) for Q, MET, and CONC follow the parameters with the respective frequencies described in DENSITY. The subroutines RNOSCS, RPROD, and RSWITCH are requested with the output presented in Figures 1-5, 1-6, and 1-7, respectively. The results are concentration and emission probabilities associated with a class limit for the respective output parameters. The class limits are those described in the CLASS package.

```
// MSGLEVEL=1,CLASS=B,TIME=1
//R EXEC FORTHLG,REGION.GO=150K,TIME.GO=1
//LKED.PROB DD DSN=FRT4610.P1686150.PROBL,DISP=SHR
//LKED.FRT DD DISP=SHR,DSN=FRT4610.P9990000.FRTLIB
//LKED.SYSLIN DD *
 INCLUDE PROB(MAIN,BLOCK,COMP,INPARM,METD,METCLA)
 INCLUDE PROB(CLASS,DENSIT,RSWITC,RPROD,TABLR,RNDSCS)
 INCLUDE FRT(HEADR,INF,ERRY,INPUT,TABLE,TXLOC)
 ENTRY MAIN
//GO.FT09F001 DD DSNAME=FRT4610.P9990000.LOGDATA,DISP=SHR
//GO.FT06F001 DD SYSOUT=A
//GO.FT05F001 DD *
PARAMETER
 &INPUT
 NC=20, ME=20, ND=20,
 GAMMA=.385, BETA=1.0, MINORM=.03
 &END
CLASS
EPS
            0.0       0.35      0.70      1.05      1.40      1.75
            2.1       2.45      2.8       3.15      3.5       3.85
            4.2       4.55      4.9       5.25      5.6       5.95
            6.3       6.65
88888
CONC
            0.0       .03       .06       .09       .12       .15
            .18       .21       .24       .27       .30       .33
            .36       .39       .42       .45       .48       .51
            .54       .57
88888
D
            0.0       .05       0.1       0.15      0.2       0.25
            0.30      0.35      0.40      0.45      0.5       0.55
            0.60      0.65      0.70      0.75      0.80      0.85
            0.9       0.95
88888
99999
DENSITY
EPS
            .437      .178      .160      .113      .056      .039
                                .009                .004

                      .004
88888
MET
                      .212      .446      .156      .078      .052
            .013      .013      .013                .004
            .004                .004
                      .004
88888
D
            .078
            .004      .009      .030      .009      .082      .035
            .026      .030      .017      .039                .437
            .182      .022

88888
99999
RNDSCS
RPROD
RSWITCH
ENDJOB
/*
```

Figure 1-4   Example of PROBL Input

```
=========================================
I   CLASS      I   CONC.      I   EMISS.   I
I     #        I      PROB.   I     PROB.  I
+-------------+-------------+-------------+
I      1.00    I0.107675     I0.078000     I
I      2.00    I0.266137     I0.0          I
I      3.00    I0.366918     I0.0          I
I      4.00    I0.154440     I0.0          I
I      5.00    I0.047466     I0.0          I
+-------------+-------------+-------------+
I      6.00    I0.019900     I0.0          I
I      7.00    I0.012909     I0.004000     I
I      8.00    I0.009867     I0.009000     I
I      9.00    I0.001150     I0.033000     I
I     10.00    I0.002960     I0.009000     I
+-------------+-------------+-------------+
I     11.00    I0.002232     I0.0          I
I     12.00    I0.001352     I0.035000     I
I     13.00    I0.001940     I0.026000     I
I     14.00    I0.000936     I0.030000     I
I     15.00    I0.000068     I0.017000     I
+-------------+-------------+-------------+
I     16.00    I0.000156     I0.039000     I
I     17.00    I0.000328     I0.082000     I
I     18.00    I0.001748     I0.457000     I
I     19.00    I0.000816     I0.182000     I
I     20.00    I0.0          I0.022000     I
+-------------+-------------+-------------+
```

Figure 1-5   RNOSCS Output Results

```
===========================================
I   CLASS       I   CONC.       I   EMISS.      I
I     #         I      PROB.    I      PROB.    I
+-------------+-------------+-------------+
I       1.00    I0.107673       I0.077920       I
I       2.00    I0.268630       I0.000015       I
I       3.00    I0.365445       I0.000015       I
I       4.00    I0.154230       I0.000044       I
I       5.00    I0.047593       I0.000096       I
+-------------+-------------+-------------+
I       6.00    I0.019562       I0.000144       I
I       7.00    I0.013608       I0.004185       I
I       8.00    I0.009314       I0.009175       I
I       9.00    I0.001788       I0.030496       I
I      10.00    I0.002628       I0.009159       I
+-------------+-------------+-------------+
I      11.00    I0.002812       I0.000676       I
I      12.00    I0.001048       I0.035688       I
I      13.00    I0.001503       I0.026182       I
I      14.00    I0.000725       I0.030125       I
I      15.00    I0.000540       I0.017259       I
+-------------+-------------+-------------+
I      16.00    I0.000096       I0.041631       I
I      17.00    I0.000202       I0.081515       I
I      18.00    I0.001075       I0.432786       I
I      19.00    I0.000502       I0.180109       I
I      20.00    I0.0            I0.021771       I
+-------------+-------------+-------------+
```

Figure 1-6   RPROD Output Results

```
=========================================
I  CLASS       I  CONC.      I  EMISS.      I
I   #          I     PROB.   I     PROB.    I
+--------------+-------------+--------------+
I      1.00    I0.107673     I0.077920      I
I      2.00    I0.266133     I0.0           I
I      3.00    I0.366912     I0.0           I
I      4.00    I0.154435     I0.0           I
I      5.00    I0.047466     I0.0           I
+--------------+-------------+--------------+
I      6.00    I0.019900     I0.0           I
I      7.00    I0.012909     I0.003996      I
I      8.00    I0.009867     I0.008991      I
I      9.00    I0.001150     I0.024970      I
I     10.00    I0.002960     I0.006991      I
+--------------+-------------+--------------+
I     11.00    I0.002232     I0.0           I
I     12.00    I0.001352     I0.034965      I
I     13.00    I0.001940     I0.025974      I
I     14.00    I0.000936     I0.029970      I
I     15.00    I0.000068     I0.016983      I
+--------------+-------------+--------------+
I     16.00    I0.000156     I0.038961      I
I     17.00    I0.000328     I0.081915      I
I     18.00    I0.001748     I0.436560      I
I     19.00    I0.000816     I0.181815      I
I     20.00    I0.0          I0.021978      I
+--------------+-------------+--------------+
```

Figure 1-7 RSWITCH Output Results

1.3 Listing of Program PROBL

MAIN PROGRAM

Subroutines (Called in Main Program):

- HEADR
- INPUT
- METDS
- MET CLASS
- DENSITY
- CLASS
- RNOSCS
- RSWITCH
- RPROD

Auxiliary Subroutines (Called in the Above Subroutines):

- PAGE
- ERRX
- INE
- INPARM
- COMP
- TXLOC
- TABLE

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```
LEVEL 21.8 ( JUN 74 )                    OS/360  FORTRAN H                                  DATE  77.111/09.33.30

        COMPILER OPTIONS - NAME=  MAIN,OPT=00,LINECNT=60,SIZE=0000K,
                           SOURCE,EBCDIC,NOLIST,NODECK,LOAD,MAP,NOEDIT,ID,NOXREF
               C      PROBABILITY ANALYSIS OF SCS METHODS
  ISN 0002            DATA ICODE/48/,VERS/1.1/,LEVEL/731511/
               C
               C    PROBABILITY TECHNIQUES DEVELOPED BY R.J. HORN AND PROF. SCHWEPPE
               C      PROGRAMMED BY RJ HORN
               C            15/11/73
               C
  ISN 0003            INTEGER KEYS(7)/'METD','METC','DENS','CLAS','RNDS','RSWI','RPRO'/
  ISN 0004            INTEGER TITLE(13)
  ISN 0005            CALL HEADR(ICODE,VERS,LEVEL)
               C
               C      READ KEYWORD CARDS
               C
  ISN 0006         10 CALL INPUT(KEYS,7,IC,IFORM,TITLE,K,&800)
  ISN 0007            GO TO (100,200,300,400,500,600,700),K
               C
               C
  ISN 0008        100 CALL METDS(IC,IFORM)
  ISN 0009            GO TO 10
               C
               C
  ISN 0010        200 CALL METCLASS(IC,IFORM)
  ISN 0011            GO TO 10
               C
               C
  ISN 0012        300 CALL DENSITY(IC,IFORM)
  ISN 0013            GO TO 10
               C
               C
  ISN 0014        400 CALL CLASS(IC,IFORM)
  ISN 0015            GO TO 10
               C
               C
  ISN 0016        500 CALL RNDSCS(IC,IFORM)
  ISN 0017            GO TO 10
               C
               C
  ISN 0018        600 CALL RSWITCH(IC,IFORM)
  ISN 0019            GO TO 10
               C
               C
  ISN 0020        700 CALL RPROD(IC,IFORM)
  ISN 0021            GO TO 10
               C
               C
  ISN 0022        800 WRITE(6,6800)
  ISN 0023       6800 FORMAT('0 END OF PROGRAM')
  ISN 0024            STOP
  ISN 0025            END
```

```
      SUBROUTINE HEADR(IC,VER,LEV)
C     ************************************************************************
C     IBM 360/85      E. REIFENSTEIN             FORTRAN IV
C     ENVIRONMENTAL RESEARCH AND TECHNOLOGY, INC., WALTHAM, MASS.
C
C     VERSION 8 LEVEL 711103
C     DOES RUN ACCOUNTING AND GENERATES PAGE HEADING
C     ************************************************************************
      REAL*8 TITLE(6)
      REAL DAT(3),DTAB(101)
      INTEGER ICODE,NLOG,IRUN,NTAB,LTAB(100),K3/1000/,
     X    K6/1000000/
      COMMON /HEAD/ TITLE,ICODE,VERS,LEVEL,DAT,IRUN,NPAGE,NLOG
      EQUIVALENCE (NTAB,DTAB(1)),(LTAB(1),DTAB(2))
      CALL DATE(DAT)
      ICODE=IC
      VERS=VER
      LEVEL=LEV
      NTAB=0
      NPAGE=0
      LINE=60
      IF(ICODE.LE.0.OR.ICODE.GE.1000.OR.NLOG.LE.0) GO TO 22
      IVERS=VERS
      REWIND NLOG
      READ(NLOG) DTAB
      DO 10 I=1,NTAB
      N3=LTAB(I)
      N1=N3/K6
      IF(N1.NE.ICODE) GO TO 10
      N3=MOD(N3,K6)
      N2=N3/K3
      IF(N2.NE.IVERS) GO TO 10
      N3=MOD(N3+1,K3)
      GO TO 20
10    CONTINUE
      IF(NTAB.GE.100) GO TO 25
      NTAB=NTAB+1
      I=NTAB
      N3=1
20    IRUN=K3*IVERS+N3
      LTAB(I)=K6*ICODE+IRUN
      REWIND NLOG
      WRITE(NLOG) DTAB
      ENDFILE NLOG
22    WRITE(6,2022) TITLE,VERS,LEVEL,IRUN,NTAB
2022  FORMAT(' BEGIN ',6A8,' VERSION',F6.2,' LEVEL ',I6,' RUN ',I6/
     X      ' TABLE COUNT=',I3///)
      RETURN
25    WRITE(6,2025)
2025  FORMAT(' LOGDATA OVERFLOW.')
      IRUN=0
      GO TO 22
      END
!PRINT ERTLPAGE
```

```
LEVEL 21.8 ( JUN 74 )                          OS/360  FORTRAN H                                      DATE  77.111/09.35.10

         COMPILER OPTIONS - NAME=  MAIN,OPT=00,LINECNT=60,SIZE=0000K,
                            SOURCE,EBCDIC,NOLIST,NODECK,LOAD,MAP,NOEDIT,ID,NOXREF
  ISN 0002             SUBROUTINE METDS(IX,IFORM)
  ISN 0003             INTEGER*4 ICLASS(6,16,8)
  ISN 0004             COMMON /METD/ ICLASS
  ISN 0005             REAL*4  NINES/'9999'/,BLANK/'    '/,KEYW
  ISN 0006             REAL*8 NAME/'METD'/
  ISN 0007             COMMON/DENS/ PLC(500),PLQ(500),PLMET(500),PLEPS(500)
  ISN 0008             REAL*4 VALUE(6)
  ISN 0009             LOGICAL IOSW
  ISN 0010             IOSW=.TRUE.
  ISN 0011             DO 50 I=1,500
  ISN 0012          50 PLMET(I)=0.
  ISN 0013          10 CONTINUE
  ISN 0014             READ(5,7000) KEYW,ISTAR,IDIR,VALUE
  ISN 0015        7000 FORMAT (A4,1X,I2,I3,6G10.5)
  ISN 0016             IF ( KEYW .EQ. NINES) GO TO 1000
  ISN 0018             DO 275 I=1,6
  ISN 0019                IC = ICLASS(I,IDIR,ISTAB)
  ISN 0020                IF ( IC .EQ. 0) GO TO 275
  ISN 0022                PLMET(IC) = PLMET(IC) + VALUE(I)
  ISN 0023         275    CONTINUE
  ISN 0024             GO TO 10
  ISN 0025        1000 RETURN
  ISN 0026             END
```

```
LEVEL 21.8 ( JUN 74 )                                    OS/360  FORTRAN H                                         DATE  77.111/09.34.11

          COMPILER OPTIONS - NAME=  MAIN,OPT=00,LINECNT=60,SIZE=0000K,
                             SOURCE,EBCDIC,NOLIST,NODECK,LOAD,MAP,NOEDIT,ID,NOXREF
   ISN 0002               SUBROUTINE METCLASS(IC,IFORM)
   ISN 0003               INTEGER*4 ICLASS(6,16,8),IDATA(3,6)
   ISN 0004               COMMON/METO/ ICLASS
   ISN 0005               REAL*4 NINES/'9999'/,EIGHTS/'8888'/,CLAS/'CLAS'/,KEYW
   ISN 0006               REAL*8  NAME/'METCLASS'/
   ISN 0007               LOGICAL IOSW
   ISN 0008               IOSW = .TRUE.
   ISN 0009                DO 5 K=1,5
   ISN 0010               DO 5 J=1,16
   ISN 0011               DO 5 I=1,6
   ISN 0012             5 ICLASS(I,J,K) = 0
   ISN 0013            10 READ(5,7000) KEYW,ICL
   ISN 0014          7000 FORMAT(A4,6X,I10)
   ISN 0015               IF(KEYW .EQ.EIGHTS) GO TO 10
   ISN 0017               IF(KEYW .EQ.NINES) GO TO 1000
   ISN 0019               IF ( KEYW .NE. CLAS) CALL ERRX(10,NAME)
   ISN 0021               WRITE (6,7010) ICL
   ISN 0022          7010 FORMAT('0',T21,'MET CLASS ',I10,5X,'CONTAINS MET CONDITIONS : '/)
   ISN 0023           100 READ(5,7005) KEYW,IDATA
   ISN 0024          7005 FORMAT(A4,6X,6(I2,1X,I3,1X,I2,1X))
   ISN 0025               IF ( KEYW .EQ. EIGHTS ) GO TO 10
   ISN 0027               IF ( KEYW .EQ. NINES) RETURN
   ISN 0029               DO 200 I=1,6
   ISN 0030               IU= IDATA(1,I)
   ISN 0031               IF(IU .EQ. 0) GO TO 200
   ISN 0033               IDIR= IDATA(2,I)
   ISN 0034               ISTAB=IDATA(3,I)
   ISN 0035               ICLASS(IU,IDIR,ISTAB) =ICL
   ISN 0036           200 CONTINUE
   ISN 0037               WRITE (6,7015) IDATA
   ISN 0038          7015 FORMAT(T11,6(I2,1X,I3,1X,I2,6X))
   ISN 0039               GO TO 100
   ISN 0040          1000 RETURN
   ISN 0041               END
```

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```
LEVEL 21.8 ( JUN 74 )                          OS/360  FORTRAN H                                    DATE  77.111/09.34.51

          COMPILER OPTIONS - NAME=  MAIN,OPT=00,LINECNT=60,SIZE=0000K,
                             SOURCE,EBCDIC,NOLIST,NODECK,LOAD,MAP,NOEDIT,ID,NOXREF
  ISN 0002            SUBROUTINE DENSITY(IC,IFORM)
  ISN 0003            COMMON/DENS/ PLC(500),PLQ(500),PLMET(500),PLEPS(500)
  ISN 0004            LOGICAL PRINT,IOSW
  ISN 0005            COMMON/PARM/ NN(3),GAMMA,BETA,MINORM,PRINT,IOSW
  ISN 0006            REAL*4 PL(500,3)
  ISN 0007            EQUIVALENCE   (PLQ(1),PL(1,1))
  ISN 0008            REAL*8 NAME/'DENSITY'/
  ISN 0009            REAL*8 EIGHTS/'8888'/,NINES/'9999'/,BLANK/'    '/
  ISN 0010            REAL*8  KEYW
  ISN 0011            REAL*8 KEYS(3)/'Q','MET','EPS'/
  ISN 0012            REAL*4 DATA(6),NAMER
  ISN 0013            IOSW=.TRUE.
  ISN 0014         10 READ(5,7000) KEYW,NAMER
  ISN 0015       7000 FORMAT(A4,6X,A4)
  ISN 0016            IF(KEYW .EQ. EIGHTS) GO TO 10
  ISN 0018            IF(KEYW .EQ. NINES) GO TO 1000
  ISN 0020            CALL TXLOC(KEYS,3,KEYW,K,&100)
  ISN 0021            GO TO 200
  ISN 0022        100 CALL ERRX(100,NAME)
  ISN 0023        200 K=K-1
  ISN 0024            IF(K .EQ. 0) K=3
  ISN 0026            NQ=NN(K)
  ISN 0027            K=K+1
  ISN 0028            IF(K .EQ. 4) K=1
  ISN 0030            NQX=1
  ISN 0031            WRITE (6,7010) KEYW
  ISN 0032       7010 FORMAT('0',T11,'PROBABILITIES FOR CLASSES OF ',A4)
  ISN 0033        250 READ(5,7005) DATA
  ISN 0034            WRITE(6,7015) DATA
  ISN 0035            DO 300 I=1,6
  ISN 0036               PL(NQX,K)=DATA(I)
  ISN 0037               NQX=NQX+1
  ISN 0038               IF(NQX.GT.NQ) GO TO 10
  ISN 0040        300 CONTINUE
  ISN 0041            GO TO 250
  ISN 0042       7005 FORMAT  (10X,6G10.5)
  ISN 0043       7015 FORMAT(T11,6(G10.4,10X))
  ISN 0044       1000 RETURN
  ISN 0045            END
```

```
LEVEL 21.8 ( JUN 74 )                          OS/360  FORTRAN H                                        DATE  77.111/09.35.18

         COMPILER OPTIONS - NAME=  MAIN,OPT=00,LINECNT=60,SIZE=0000K,
                            SOURCE,EBCDIC,NOLIST,NODECK,LOAD,MAP,NOEDIT,ID,NOXREF
  ISN 0002               SUBROUTINE RNOSCS(IC,IFORM)
  ISN 0003               LOGICAL IOSW,PRINT
  ISN 0004               COMMON/PARM/NC,NE,NQ,GAMMA,BETA,MINORM,PRINT,IOSW
  ISN 0005               REAL*4 LIMITC(500),LIMITE(500),LIMITQ(500),CENTRC(500),
                        1    CENTRE(500),CENTRQ(500)
  ISN 0006               COMMON /XCLASS/ LIMITC,LIMITE,LIMITQ,CENTRC,CENTRE,CENTRQ
  ISN 0007               REAL*4 TABS(500,3)
  ISN 0008               REAL*8 FH(3,2),FD(3)
  ISN 0009               COMMON/FORMS/FD,FH
  ISN 0010               COMMON/DENS/ PLC(500),PLQ(500),PLMET(500),PLEPS(500)
  ISN 0011               NM=NC
  ISN 0012               DO 50 I=1,500
  ISN 0013        50         PLC(I) = 0.
  ISN 0014               DO 1000 I=1,NQ
  ISN 0015               DO 1000 J=1,NM
  ISN 0016                   CONC=CENTRQ(I)*CENTRC(J)
  ISN 0017               DO 400 K=2,NC
  ISN 0018                   IF ( CONC .LT. LIMITC(K)) GO TO 500
  ISN 0020        400         CONTINUE
  ISN 0021               K=NC+1
  ISN 0022        500    K=K-1
  ISN 0023               PLC(K) = PLC(K) + PLQ(I)*PLMET(J)
  ISN 0024        1000   CONTINUE
  ISN 0025               IF ( NQ .GT. NC) NZ=NQ
  ISN 0027               IF ( NQ .LE. NC) NZ=NC
  ISN 0029               DO 2000 I=1,N7
  ISN 0030                   TABS(I,2)=0.
  ISN 0031                   TABS(I,3)=0.
  ISN 0032        2000       TABS(I,1)=I
  ISN 0033               DO 3000 I=1,NQ
  ISN 0034        3000       TABS(I,3)=PLQ(I)
  ISN 0035               DO 4000 I=1,NC
  ISN 0036        4000       TABS(I,2) = PLC(I)
  ISN 0037               CALL TABLE(TABS,500,3,NZ,3,FH,2,FD,5)
  ISN 0038               RETURN
  ISN 0039               END
```

```
      SUBROUTINE PAGE
C     *****************************************************************
C     PRINTS PAGE HEADER AND KEEPS TRACK OF LINE COUNT
C             VERSION 2.0 LEVEL 750905
C     *****************************************************************
      INTEGER ICODE,IRUN,NPAGE
      REAL*8 TITLE(6)
      REAL DATE(3),VERS
      COMMON /HEAD/ TITLE,ICODE,VERS,LEVEL,DATE,IRUN,NPAGE,NLOG
      INTEGER LCT/61/
      K=1
      LINE=4
      GO TO 30
C     -----------------------------------------------------------------
      ENTRY LINES(N,*)
      K=0
      LINE=LINE+N
      IF(LINE.LT.LCT.AND.LCT.GT.0)  RETURN
      LINE=N+4
30    NPAGE=NPAGE+1
      WRITE(6,2030) ICODE,IRUN,TITLE,VERS,LEVEL,DATE,NPAGE
2030  FORMAT('1',I3,I6,4X,6A8,' VERSION ',F6.2,'  (',I6,')',11X,
     X   3A4,10X,'PAGE',I3/1X,127('*'))
      IF(K.EQ.0) RETURN 1
      RETURN
C     -----------------------------------------------------------------
      ENTRY LSET(N)
      LCT=N
      RETURN
C
C     -----------------------------------------------------------------
      ENTRY LINENO(M)
      M=LINE
      RETURN
C     -----------------------------------------------------------------
      END
!EOF
BATCH TERMINATED: 10/04/77   11:58:34
```

```
//ERRX EXEC FORTGC,PARM.FORT='LOAD'
//FORT.SYSLIN DD DSN=ERT4610.P9990000.ERTLIB(ERRX),DISP=OLD,SPACE=
//FORT.SYSIN DD *
      SUBROUTINE ERRX(N,NAME)
C     ******************************************************************
C     IBM 360                E.REIFENSTEIN                   FORTRAN IV
C     TERMINATES EXECUTION DUE TO NUMBERED ERROR(N) IN NAMED ROUTINE
C      VERSION 2   LEVEL 711115
C     ******************************************************************
      INTEGER N
      REAL*8 NAME
      WRITE(6,6000)   N,NAME
 6000 FORMAT('0EXECUTION TERMINATED DUE TO ERROR NO. ',I4,' IN ',A8)
      STOP
C     ******************************************************************
C......ENTRY ERRM ISSUES A NON FATAL ERROR MESSAGE AND RETURNS TO
C......A USER SELECTED STATEMENT NUMBER.
C     ******************************************************************
       ENTRY ERRM(N,NAME,*)
       WRITE(6,6100) N,NAME
6100   FORMAT('0ERROR NUMBER ',I4,' IN ',A8/)
       RETURN 1
C
      END
!PRINT ERTLTABLE
```

```
       SUBROUTINE TXLUC(TT,NT,X,IX,*)
C*********************************************************************
C      IMPACT VERSION 1.0   LEVEL 711229
C*********************************************************************
C
       REAL*8 TT(1),X
       IX=0
C
       DO 100 N=1,NT
       IF (X.EQ.TT(N)) GO TO 200
100    CONTINUE
C
       RETURN 1
C
200    IX=N
       RETURN
       END
!PRINT ERTLERRX
```

```
//ERRX EXEC FORTHC,PARM.FORT='LOAD'
//FORT.SYSLIN DD DSN=ERT4610.P9990000.ERTLIB(INE),DISP=OLD,SPACE=
//FORT.SYSIN DD *
      SUBROUTINE INE(IC,PRINT)
C     *******************************************************************
C     READS AND PRINTS COMMENTS CARDS
C     MARTIK VERSION 2.3   LEVEL 711115
C     *******************************************************************
      REAL*8 NAME/'INE'/
      LOGICAL PRINT
      INTEGER IFORM,IF(3)/' ','0','1'/,COM(13),BLANK/' '/
   10 READ(IC,5010)   IFORM,COM,JF
 5010 FORMAT(14X,A1,5X,12A4,A2,A2)
      IF(.NOT.PRINT)   GO TU 50
      DO 20   I=1,3
      IF(IFORM.EQ.IF(I))   GO TO (30,30,40),I
   20 CONTINUE
      CALL ERRX(20,NAME)
   30 CALL LINES(I,&32)
   32 WRITE(6,6032)   IF(I),COM
 6032 FORMAT(A1,T21,12A4,A2)
      GO TO 50
   40 CALL PAGE
      I=2
      GO TO 30
   50 IF(JF.NE.BLANK)   GU 10 10
      RETURN
      END
!EOF
BATCH TERMINATED: 10/03/77   14:28:50
```

```
LEVEL 21.8 ( JUN 74 )                         OS/360  FORTRAN H                                        DATE  77.111/09.35.03

          COMPILER OPTIONS - NAME=  MAIN,OPT=00,LINECNT=60,SIZE=0000K,
                             SOURCE,EBCDIC,NOLIST,NODECK,LOAD,MAP,NOEDIT,ID,NOXREF
  ISN 0002                SUBROUTINE COMP(IC,IFORM)
  ISN 0003             RETURN
  ISN 0004             END
```

```
LEVEL 21.8 ( JUN 74 )                          OS/360  FORTRAN H                            DATE  77.111/09.34.25

       COMPILER OPTIONS - NAME=  MAIN,OPT=00,LINECNT=60,SIZE=0000K,
                          SOURCE,EBCDIC,NOLIST,NODECK,LOAD,MAP,NOEDIT,ID,NOXREF
  ISN 0002            SUBROUTINE INPARM(IC,TITLE,JF)
  ISN 0003            REAL*8 NAME/'INPARM'/
  ISN 0004            LOGICAL PRINT,IOSW
  ISN 0005            COMMON /PARM/ NC,NE,NQ,GAMMA,BETA,HINORM,PRINT,IOSW
  ISN 0006            NAMELIST/INPUT/ NC,NE,NQ,GAMMA,BETA,HINORM,PRINT,IOSW
  ISN 0007            BETOLD=BETA
  ISN 0008            READ(5,INPUT,END=800)
  ISN 0009            IF( BETA .NE. BETOLD) IOSW=.TRUE.
  ISN 0011            WRITE(6,INPUT)
  ISN 0012            RETURN
  ISN 0013        800 CALL ERRX(800,NAME)
  ISN 0014            STOP
  ISN 0015            END
```

```
LEVEL 21.8 ( JUN 74 )                    OS/360  FORTRAN H                                DATE  77.111/09.33.43

           COMPILER OPTIONS - NAME=  MAIN,OPT=00,LINECNT=60,SIZE=0000K,
                              SOURCE,EBCDIC,NOLIST,NODECK,LOAD,MAP,NOEDIT,ID,NOXREF
  ISN 0002          SUBROUTINE CLASS(IC,IFORM)
  ISN 0003          REAL*4 LIMITC(500),LIMITF(500),LIMITQ(500),CENTRC(500),
                   1    CENTRE(500),CENTRQ(500)
  ISN 0004          REAL*4 LIMIT(500,3),CENTER(500,3)
  ISN 0005          EQUIVALENCE(LIMIT(1,1),LIMITC(1))
  ISN 0006          EQUIVALENCE (CENTER(1,1),CENTRC(1))
  ISN 0007          COMMON/XCLASS/LIMIT,CENTER
  ISN 0008          LOGICAL PRINT,IOSW
  ISN 0009          COMMON /PARM/ NN(3),GAMMA,BETA,HINORM,IPRINT,IOSW
  ISN 0010          REAL*8 KEYS(1)/'NORM'/,NAMES(3)/'CONC','EPS','Q'/,NAME/'CLASS'/
  ISN 0011          REAL*8 EIGHTS/'8888'/,NINES/'9999'/,BLANK/'    '/
  ISN 0012          REAL*8 NAMER,KEYW
  ISN 0013          REAL*4 DATA(6)
  ISN 0014          REAL*4 LOWLIM
  ISN 0015          IOSW=.TRUE.
  ISN 0016       10 READ(5,7000) KEYW,NAMER
  ISN 0017     7000 FORMAT (A4,6X,A4)
  ISN 0018          IF (KEYW .EQ. EIGHTS) GO TO 10
  ISN 0020          IF (KEYW .EQ. NINES) GO TO 1000
  ISN 0022          CALL TXLOC(NAMES,3,KEYW,I1,&100)
  ISN 0023          GO TO 200
  ISN 0024      100 CALL ERRX(100,NAME)
                C
                C      INPUT CLASS LIMITS
                C
  ISN 0025      200 NDX=1
  ISN 0026          NQ=NN(I1)
  ISN 0027          WRITE(6,7010) KEYW
  ISN 0028     7010  FORMAT ('0  CLASS LIMITS OF ',A4)
  ISN 0029      210 READ (5,7005) KEYW,DATA
  ISN 0030     7005 FORMAT(A4,6X,6G10.5)
  ISN 0031          IF (KEYW .EQ. EIGHTS) GO TO 360
  ISN 0033          IF (KEYW .EQ. NINES) GO TO 360
  ISN 0035          IF (KEYW .NE. BLANK) CALL ERRX(250,NAME)
  ISN 0037          WRITE (6,7015) DATA
  ISN 0038     7015 FORMAT(T11,6(G10.4,10X))
  ISN 0039          DO  350 I=1,6
  ISN 0040              LIMIT(NDX,I1)=DATA(I)
  ISN 0041              NDX=NDX+1
  ISN 0042              IF(NDX .GT. NQ ) GO TO 360
  ISN 0044      350 CONTINUE
  ISN 0045          GO TO 210
                C
                C       CALCULATE CENTER VALUE FOR EACH CLASS
                C
  ISN 0046      360 DO 375 I=1,NQ
  ISN 0047          LOWLIM=LIMIT(I,I1)
  ISN 0048          IF ( I .EQ. NQ) HILIM=LIMIT(NQ,I1) + HINORM
  ISN 0050          IF(I.NE.NQ) HILIM= LIMIT(I+1,I1)
  ISN 0052          CENTER(I,I1)= (LOWLIM+HILIM)/2.
  ISN 0053      375 CONTINUE
  ISN 0054          IF (KEYW .EQ. NINES) GO TO 1000
  ISN 0056          GO TO 10
  ISN 0057     1000 RETURN
  ISN 0058          END
```

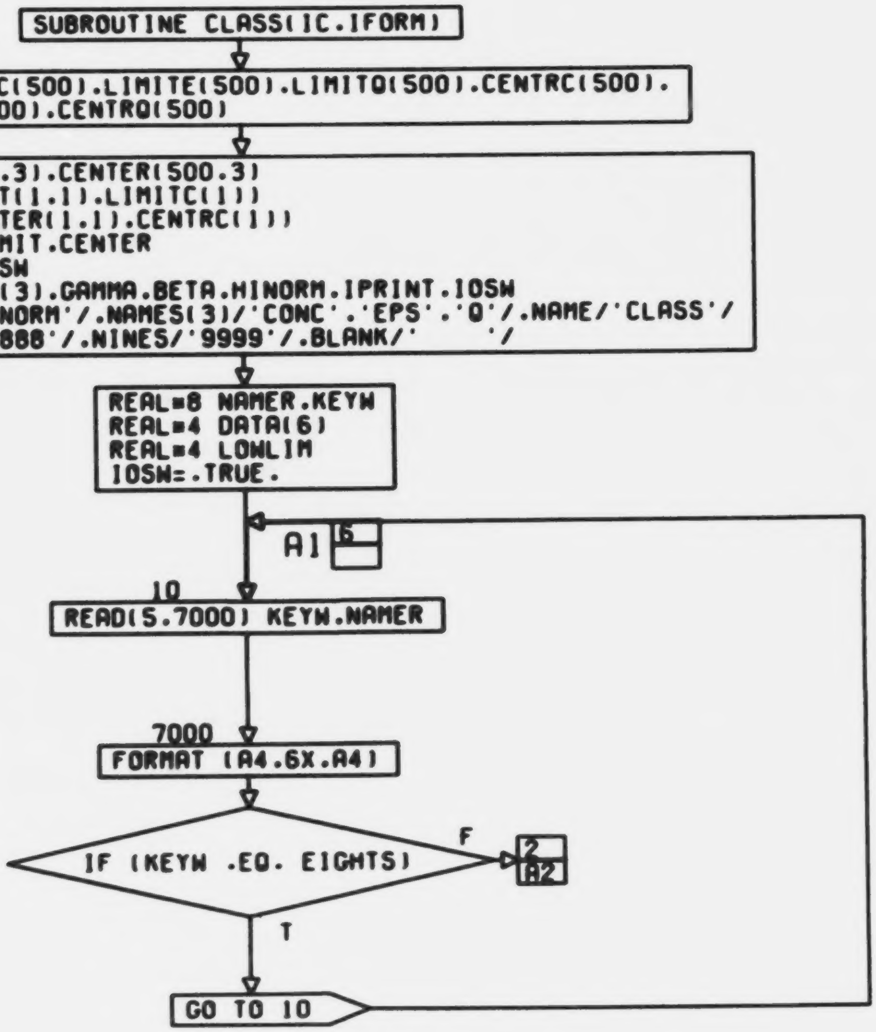
```
LEVEL 21.8 ( JUN 74 )                          OS/360  FORTRAN H                                    DATE  77.111/09.35.33

        COMPILER OPTIONS - NAME=  MAIN,OPT=00,LINECNT=60,SIZE=0000K,
                          SOURCE,EBCDIC,NOLIST,NODECK,LOAD,MAP,NOEDIT,ID,NOXREF
  ISN 0002              SUBROUTINE RPROD(IX,IFORM)
  ISN 0003              LOGICAL IOSW,PRINT
  ISN 0004              COMMON/PARM/NC,NE,NQ,GAMMA,BETA,MINORM,PRINT,IOSW
  ISN 0005              REAL*8 FH(2,3),FD(3)
  ISN 0006              COMMON/FORMS/FD,FH
  ISN 0007              REAL*4 LIMITC(500),LIMITE(500),LIMITQ(500),CENTRC(500),
                       1    CENTRE(500),CENTRQ(500)
  ISN 0008              COMMON /XCLASS/ LIMITC,LIMITE,LIMITQ,CENTRC,CENTRE,CENTRQ
  ISN 0009              COMMON/TABLS/PMQ(500),PBMQ(500),CPMQ(500),CPGE(500),CPMQE(500),
                       1    CPME(500)
  ISN 0010              COMMON/DENS/PLC(500),PLQ(500),PLMET(500),PLEPS(500)
  ISN 0011              REAL*4 XNPC(500),XNPQ(500)
  ISN 0012              REAL*4 TABS(500,3)
  ISN 0013              DO 10 I=1,500
  ISN 0014              XNPC(I)=0.
  ISN 0015        10    XNPQ(I)=0.
  ISN 0016              PEV=0.
  ISN 0017              DO 1000 I=1,NC
  ISN 0018              DO 1000 J=1,NQ
  ISN 0019              DO 1000 K=1,NE
                  C
  ISN 0020              PEV=PLMET(I)*PLQ(J)*PLEPS(K)
  ISN 0021              QME=CENTRC(I)*CENTRQ(J)*CENTRE(K)
  ISN 0022              IF ( QME .GE. GAMMA) GO TO 500
                  C
                  C     NO REDUCTION
                  C
  ISN 0024              IQ=J
  ISN 0025              XC=CENTRC(I)*CENTRQ(J)
  ISN 0026              DO 200  IC=2,NC
  ISN 0027                 IF( XC .LT. LIMITC(IC)) GO TO 250
  ISN 0029        200   CONTINUE
  ISN 0030              IC=NC+1
  ISN 0031        250   IC=IC-1
  ISN 0032              XNPC(IC) = XNPC(IC) + PEV
  ISN 0033              XNPQ(IQ) = XNPQ(IQ) + PEV
  ISN 0034              GO TO 1000
                  C
                  C     REDUCTION PROB
                  C
  ISN 0035        500   XQ=GAMMA/(CENTRC(I)*CENTRE(K))
  ISN 0036              DO 700 IQ=2,NQ
  ISN 0037                 IF( XQ .LT. LIMITQ(IQ)) GO TO 750
  ISN 0039        700   CONTINUE
  ISN 0040              IQ=NQ+1
  ISN 0041        750   IQ=IQ-1
  ISN 0042              XC= GAMMA/CENTRE(K)
  ISN 0043              DO 900 IC=2,NC
  ISN 0044                 IF( XC .LT. LIMITC(IC)) GO TO 950
  ISN 0046        900   CONTINUE
  ISN 0047              IC=NC+1
  ISN 0048        950   IC=IC-1
  ISN 0049              XNPC(IC) = XNPC(IC) + PEV
  ISN 0050              XNPQ(IQ) = XNPQ(IQ) + PEV
                  C
  ISN 0051        1000  CONTINUE

                                                                                                        PAGE 002

                  C
                  C     OUTPUT RESULTS : CLASS,XNPC,XNPQ
                  C
  ISN 0052              DO 2500 I=1,500
  ISN 0053              TABS(I,1) = 0.
  ISN 0054              TABS(I,2) = 0.
  ISN 0055              TABS(I,3) = 0.
  ISN 0056        2500  CONTINUE
  ISN 0057              IF(NQ .GT. NC) NMAX=NQ
  ISN 0059              IF(NC .GE. NQ) NMAX=NC
  ISN 0061              DO 3000 I=1,NMAX
  ISN 0062              TABS(I,1) = I
  ISN 0063              IF( I .GT. NC) GO TO 2100
  ISN 0065              TABS(I,2) = XNPC(I)
  ISN 0066        2100  IF(I .GT. NQ) GO TO 3000
  ISN 0068              TABS(I,3) = XNPQ(I)
  ISN 0069        3000  CONTINUE
                  C
                  C     WRITE
                  C
  ISN 0070              CALL TABLE(TABS,500,3,NMAX,3,FH,2,FD,5)
  ISN 0071              RETURN
  ISN 0072              END
```

```
LEVEL 21.8 ( JUN 74 )                          OS/360  FORTRAN H                                    DATE  77.111/09.33.56

          COMPILER OPTIONS - NAME=  MAIN,OPT=00,LINECNT=60,SIZE=0000K,
                            SOURCE,EBCDIC,NOLIST,NODECK,LOAD,MAP,NOEDIT,ID,NOXREF
  ISN 0002              SUBROUTINE RSWITCH(IC,IFORM)
  ISN 0003              REAL*8 FH(2,3),FD(3)
  ISN 0004              COMMON /FORMS/FD,FH
  ISN 0005              COMMON/TABLS/PMQ(500),PBMQ(500),CPMQ(500),CPGE(500),CPMOE(500),
                       1     CPME(500)
  ISN 0006              REAL*4 LIMITC(500),LIMITE(500),LIMITQ(500),CENTRC(500),
                       1     CENTRE(500),CENTRQ(500)
  ISN 0007              COMMON /XCLASS/ LIMITC,LIMITE,LIMITQ,CENTRC,CENTRE,CENTRQ
  ISN 0008              LOGICAL PRINT,IOSW
  ISN 0009              COMMON /PARM/ NC,NE,NQ,GAMMA,BETA,MINORM,PRINT,IOSW
  ISN 0010              COMMON/DENS/PLC(500),PLQ(500),PLMET(500),PLEPS(500)
  ISN 0011              REAL*4 XNPC(500),XNPQ(500)
  ISN 0012              REAL*4 TABS(500,3)
  ISN 0013              DO 10 I=1,500
  ISN 0014              XNPC(I) = 0.
  ISN 0015              XNPQ(I) = 0.
  ISN 0016           10 CONTINUE
  ISN 0017              DO 1000 I=1,NC
  ISN 0018              DO 1000 J=1,NQ
  ISN 0019              DO 1000 K=1,NE
                  C
  ISN 0020              PEV=PLMET(I)*PLQ(J)*PLEPS(K)
  ISN 0021              QME=CENTRC(I)*CENTRQ(J)*CENTRE(K)
  ISN 0022              IF ( QME .GE. GAMMA) GO TO 500
                  C
                  C   NO SWITCH
                  C
  ISN 0024              IQ=J
  ISN 0025              XC=CENTRQ(J)*CENTRC(I)
  ISN 0026              DO 200 IC=2,NC
  ISN 0027              IF (XC.LT.LIMITC(IC)) GO TO 250
  ISN 0029          200 CONTINUE
  ISN 0030              IC=NC+1
  ISN 0031          250 IC=IC-1
  ISN 0032              XNPC(IC) = XNPC(IC) + PEV
  ISN 0033              XNPQ(IQ) = XNPQ(IQ) + PEV
  ISN 0034              GO TO 1000
                  C
                  C   SWITCH PROBS
                  C
  ISN 0035          500 XQ=BETA*CENTRQ(J)
  ISN 0036              DO 700 IQ=2,NQ
  ISN 0037                  IF( XQ .LT. LIMITQ(IQ)) GO TO 750
  ISN 0039          700 CONTINUE
  ISN 0040              IQ=NQ+1
  ISN 0041          750 IQ=IQ-1
  ISN 0042              XC= BETA*CENTRC(I)*CENTRQ(J)
  ISN 0043              DO 900 IC=2,NC
  ISN 0044                  IF( XC .LT. LIMITC(IC)) GO TO 950
  ISN 0046          900 CONTINUE
  ISN 0047              IC=NC+1
  ISN 0048          950 IC=IC-1
  ISN 0049              XNPC(IC) = XNPC(IC) + PEV
  ISN 0050              XNPQ(IQ) = XNPQ(IQ) + PEV
                  C***  END OF LOOP
  ISN 0051         1000 CONTINUE


                                                                                                         PAGE 002

                  C
                  C     PRINT RESULTS , CLASS ,XNPC , XNPQ
                  C
  ISN 0052              DO 2500 I=1,500
  ISN 0053                  TABS(I,1) = I
  ISN 0054                  TABS(I,2) = 0.
  ISN 0055                  TABS(I,3) = 0.
  ISN 0056         2500 CONTINUE
  ISN 0057              IF (NQ .GT. NC) NMAX=NQ
  ISN 0059              IF (NC .GE. NQ) NMAX=NC
  ISN 0061              DO 3000 I=1,NMAX
  ISN 0062              IF ( I .GT. NC) GO TO 2100
  ISN 0064              TABS(I,2) = XNPC(I)
  ISN 0065         2100 IF( I .GT. NQ) GO TO 3000
  ISN 0067              TABS(I,3) = XNPQ(I)
  ISN 0068         3000 CONTINUE
                  C
                  C     WRITE
                  C
  ISN 0069              CALL TABLE(TABS,500,3,NMAX,3,FH,2,FD,5)
  ISN 0070              RETURN
  ISN 0071              END
```

```
      SUBROUTINE INPUT(KEYS,N,IC,IFORM,TITLE,K,*)
C***********************************************************************
C     IBM 360          E. REIFENSTEIN          FORTRAN IV
C     VERSION 1        720623
C***********************************************************************
C
      REAL*8 NAME/'INPUT'/
      INTEGER KEYS(N),IC,IFORM,K,TITLE(13),JF,KEY(3),
     X      .   KEYW(5)/'PARA','COMM','COMP','ENDJ','9999'/,
     X          BLANK/'    '/
C***********************************************************************
C
10    READ(5,5010,END=800) KEY,IC,IFORM,TITLE,JF
5010  FORMAT(3A4,2I3,2X,12A4,2A2)
C
      IF (IC) 20,49,22
C
20    IC=-IC
      REWIND IC
C
22    CALL PAGE
      CALL LINES(4,&25)
25    WRITE   (6,6025) IC,TITLE
6025  FORMAT(/T21,'TAPE',I2,T31,'LABEL=',12A4,A2//)
      IF(JF.NE.BLANK) CALL INE(IC,.TRUE.)
C
      READ(IC,5010,END=800) KEY,K,IFORM,TITLE,JF
      GO TO 50
C
49    IC=5
C
50    DO 60 K=1,5
      IF(KEY(1).EQ.KEYW(K))    GO TO(100,200,300,400,10),K
60    CONTINUE
C
      DO 80 K=1,N
      IF(KEY(1).EQ.KEYS(K)) GO TO 90
80    CONTINUE
C
      CALL ERRX(80,NAME)
C
90    IF(IC.EQ.5)      CALL PAGE
      WRITE(6,6090) KEY,TITLE,IC
6090  FORMAT(/T2,3A4,T21,12A4,A2,T81,'(UNIT ',I2,')'/)
      CALL LINES(3,&95)
C
95    RETURN
C
100   CALL INPARM(IC,TITLE,JF)
      GO TO 10
C
200   CALL INE(IC,.TRUE.)
      GO TO 10
C
300   IF(IC.EQ.5)      CALL PAGE
      WRITE(6,6300) TITLE,IC,IFORM
6300  FORMAT(/T21,12A4,A2,T81,'(UNIT ',I2,')'//T21,'COMPUTATIONS ',
     X         'PERFORMED BY ROUTINE ',I5/)
C
      CALL LINES(5,&350)
350   CALL COMP(IC,IFORM)
      GO TO 10
C
800   CALL ERRM(800,NAME,&400)
400   RETURN 1
      END
!PRINT ERTLTXLOC
```

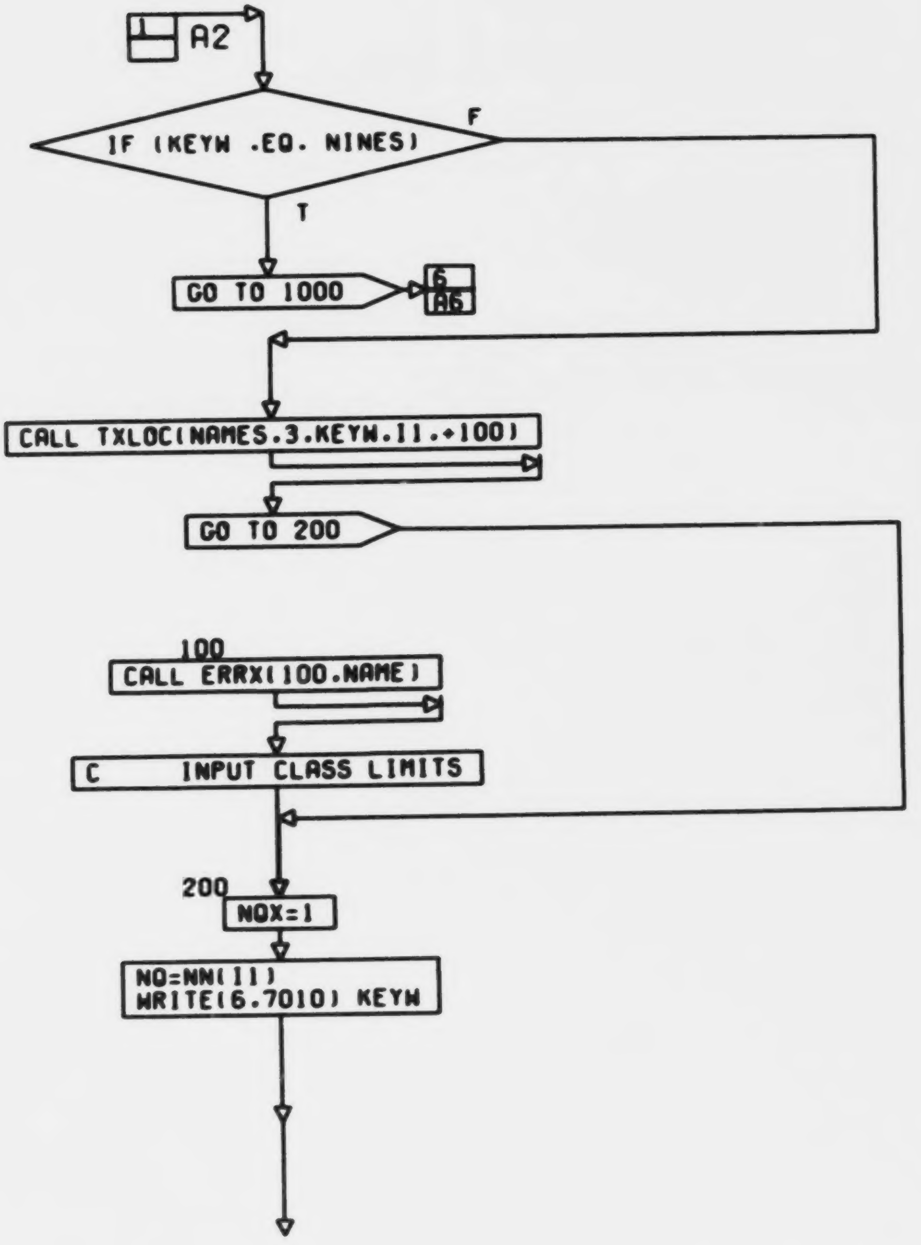
```
//  MSGLEVEL=1,CLASS=B
//A EXEC FORTHC,PARM.FORT='UPTC=2,LOAD'
//FORT.SYSLIN DD DSN=ERT4610.P9990000.ERTLIB(TABLE),DISP=OLD,SPACE=
//FORT.SYSIN DD *
      SUBROUTINE TABLE(X,NR,NC,KR,KC,FH,KH,FD,KD)
C     ******************************************************************
C     IBM 360                  E.REIFENSTEIN                    FORTRAN IV
C     ENVIRONMENTAL RESEARCH AND TECHNOLOGY,INC.,WALTHAM,MASS
C
C     VERSION 2S    LEVEL 71075     (SPECIAL CHARACTERS)
C     INPUTS--
C        X=ARRAY TO BE TABULATED(NR,NC)
C        NR=MAX NUMBER OF ROWS(ROW-DIMENSION OF X IN MAIN)
C        NC=MAX NUMBER OF COLUMNS(COL-DIMENSION IN MAIN)
C        KR=NUMBER OF ROWS TO BE PRINTED
C        KC=NUMBER OF COLUMNS TO BE PRINTED
C        FH=ARRAY OF 8-BYTE HEADING FORMATS(DIMENSIONED (KC,KH))
C        KH=NUMBER OF ROWS OF COLUMN HEADINGS
C        FD=ARRAY OF 8-BYTE DATA FORMATS(DIMENSIONED(NC))
C        KD=NUMBER OF ROWS BETWEEN HORIZONTAL LINES
C     METHOD--COMPUTES OBJECT-TIME FORMATS FOR COLUMN HEADINGS,VERTICAL
C        AND HORIZONTAL LINES,AND TABULATED DATA.
C     ******************************************************************
      REAL*4 X(NR,NC)
      REAL*8 FH(NC,KH),FD(NC)
      REAL*8 TAB(11)/'T2,A1,','T15,A1,','T28,A1,','T41,A1,',
     X   'T54,A1,','T67,A1,','T80,A1,','T93,A1,','T106,A1,',
     X   'T119,A1,','T132,A1,'/,TT
      REAL*8 FMT(23)/'(',21*' ','1X)'/,GMT(23)/'(',21*' ','1X)'/,
     X   HMT(23)/'(',21*' ','1X)'/,FF/'2X,A8,'/,GG/' '/,HH/'3A4,A1,'/
      INTEGER VLINE/'I'/,TLINE/'='/,CROSS/'+'/,HBAR(3)/3*'----'/,
     X   TBAR(4)/4*'===='/
      IF(KC.GT.10)   KC=10
C     BLANK OUT OLD FORMATS
      DO 5   I=2,22
      FMT(I)=GG
      GMT(I)=GG
    5 HMT(I)=GG
C     COMPUTE NEW FORMATS
      K =(10-KC)/2+1
      TT=TAB(K)
      HMT(2)=TT
      J=2
      DO 10   I=1,KC
      FMT(J)=TT
      GMT(J)=TT
      FMT(J+1)=FF
      GMT(J+1)=FD(I)
      HMT(I+2)=HH
      J=J+2
      K=K+1
   10 TT=TAB(K)
   20 FMT(J)=TT
      GMT(J)=TT
      I=0
C     WRITE COLUMN HEADINGS
   30 CALL LINES(KH+2,&35)
   35 WRITE(6,HMT)  TLINE,(TBAR,J=1,KC)
      DO 40   K=1,KH
   40 WRITE(6,FMT) VLINE,(FH(J,K),VLINE,J=1,KC)
   50 WRITE(6,HMT)  CROSS,(HBAR,CROSS,J=1,KC)
      CALL LINES(KD+1,&30)
      DO  60   K=1,KD
      I=I+1
      WRITE(6,GMT)  VLINE,(X(I,J),VLINE,J=1,KC)
      IF(I.GE.KR)   GO TO 70
   60 CONTINUE
      GO TO 50
   70 CALL LINES(K-KD,&75)
   75 WRITE(6,HMT) CROSS,(HBAR,CROSS,J=1,KC)
      RETURN
      END
!PRINT ERTLINE
```

1.4 Program Flow Chart



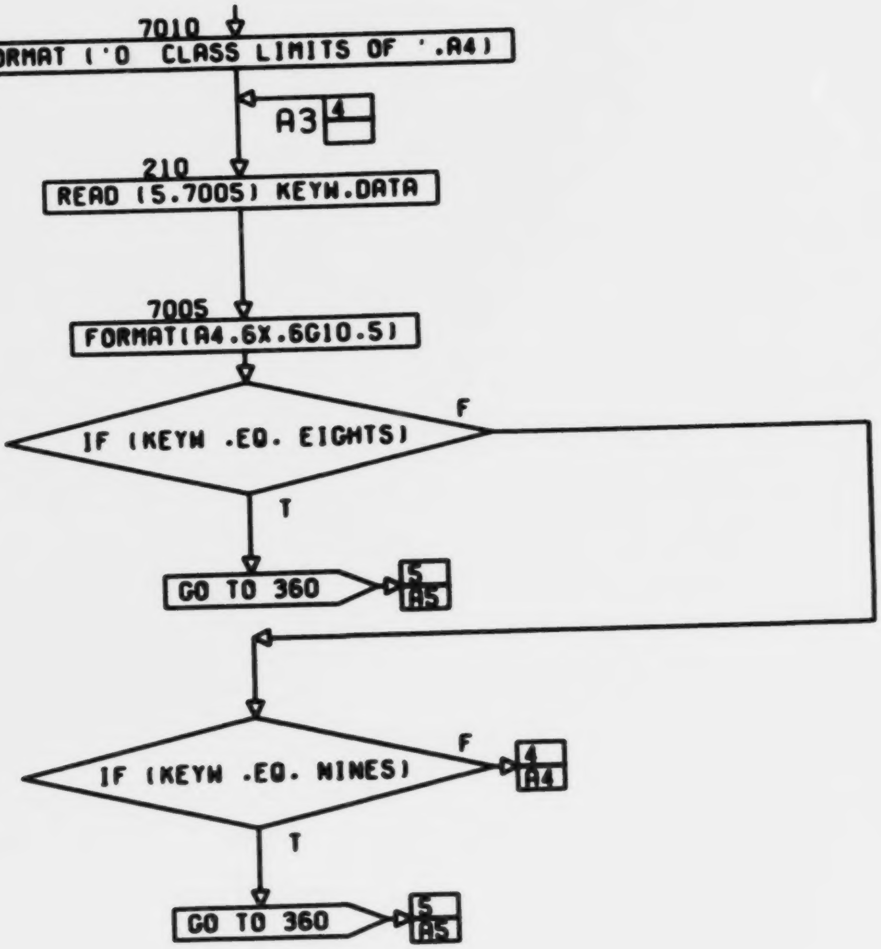
```
SUBROUTINE CLASS(IC.IFORM)
REAL*4 LIMITC(500).LIMITE(500).LIMITQ(500).CENTRC(500).
     CENTRE(500).CENTRQ(500)
REAL*4 LIMIT(500.3).CENTER(500.3)
EQUIVALENCE(LIMIT(1.1).LIMITC(1))
EQUIVALENCE (CENTER(1.1).CENTRC(1))
COMMON/XCLASS/LIMIT.CENTER
LOGICAL PRINT.IOSW
COMMON /PARM/ NN(3).GAMMA.BETA.MINORM.IPRINT.IOSW
REAL*8 KEYS(1)/'NORM'/.NAMES(3)/'CONC'.'EPS'.'Q'/.NAME/'CLASS'/
REAL*8 EIGHTS/'8888'/.NINES/'9999'/.BLANK/'    '/
REAL*8 NAMER.KEYW
REAL*4 DATA(6)
REAL*4 LOWLIM
IOSW=.TRUE.
10   READ(5.7000) KEYW.NAMER
7000 FORMAT (A4.6X.A4)
IF (KEYW .EQ. EIGHTS)
GO TO 10
```

PG 1 OF 6

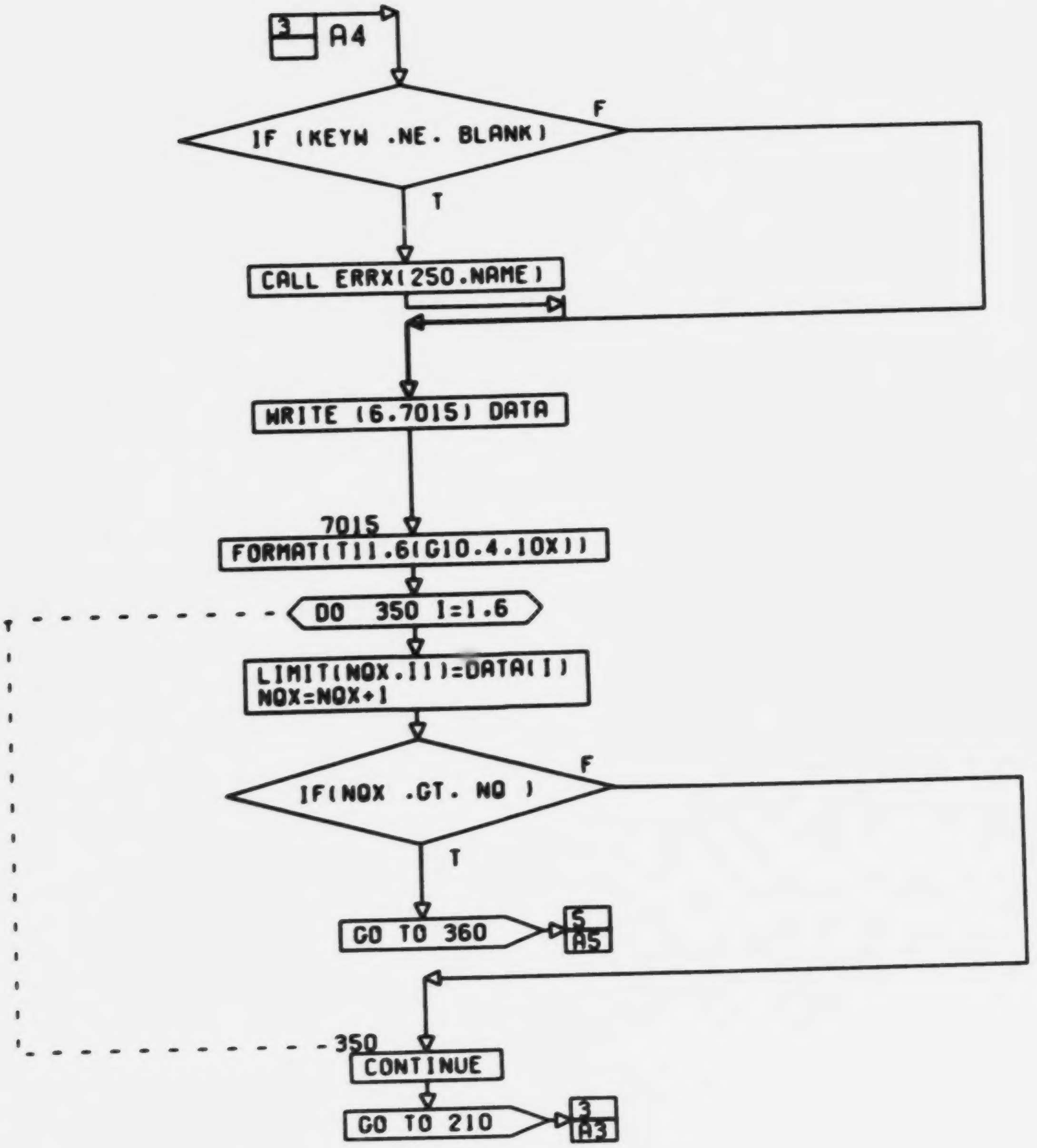


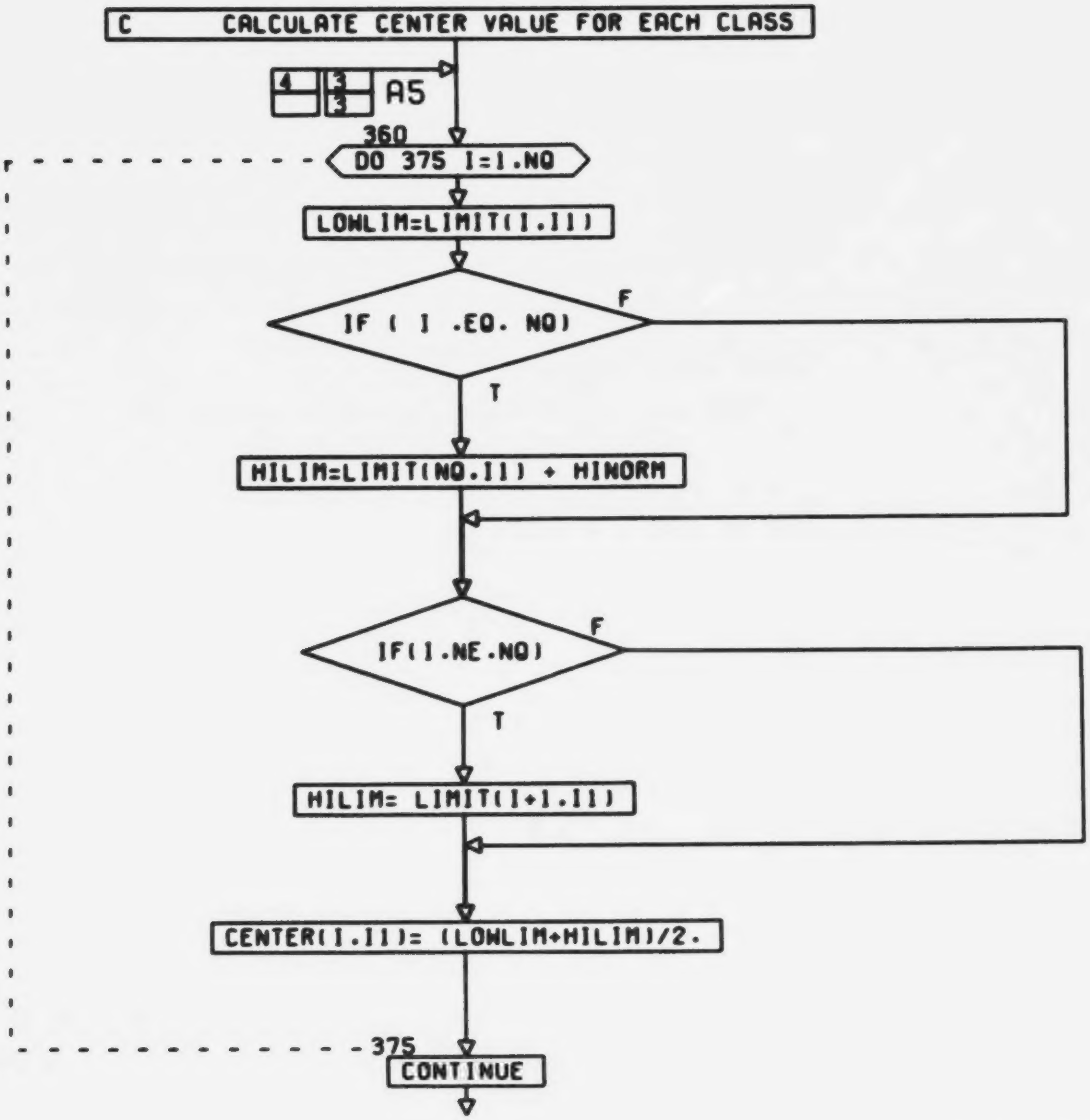
1
A2
IF (KEYW .EQ. NINES)
F
T
GO TO 1000
6
A6
CALL TXLOC(NAMES.3.KEYW.I1.+100)
GO TO 200
100
CALL ERRX(100.NAME)
C INPUT CLASS LIMITS
200
NOX=1
NO=NN(I1)
WRITE(6.7010) KEYW

PG 2 OF 6

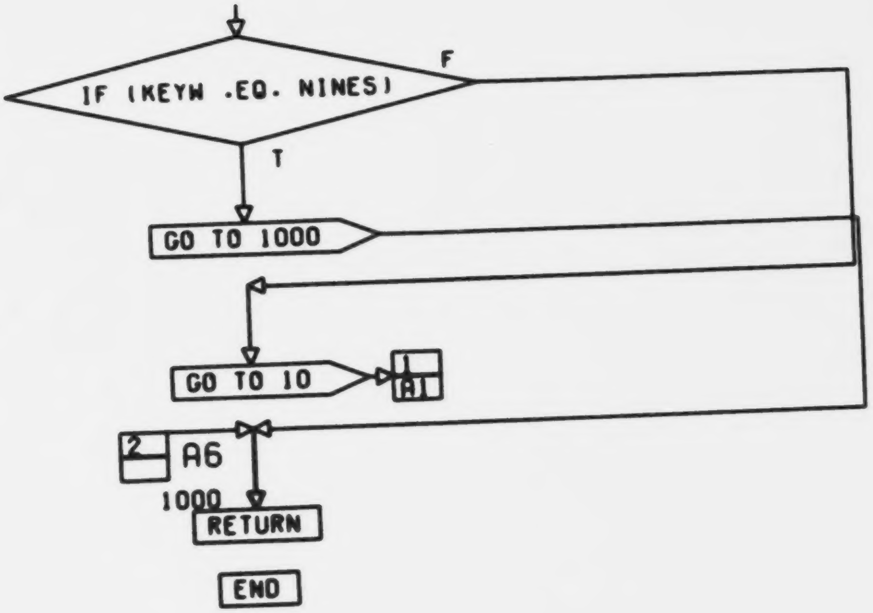

7010
FORMAT ('0 CLASS LIMITS OF '.A4)
A3
4
210
READ (5.7005) KEYW.DATA
7005
FORMAT(A4.6X.6G10.5)
IF (KEYW .EQ. EIGHTS)
F
T
GO TO 360
5
A5
IF (KEYW .EQ. NINES)
F
4
A4
T
GO TO 360
5
A5

PG 3 OF 6

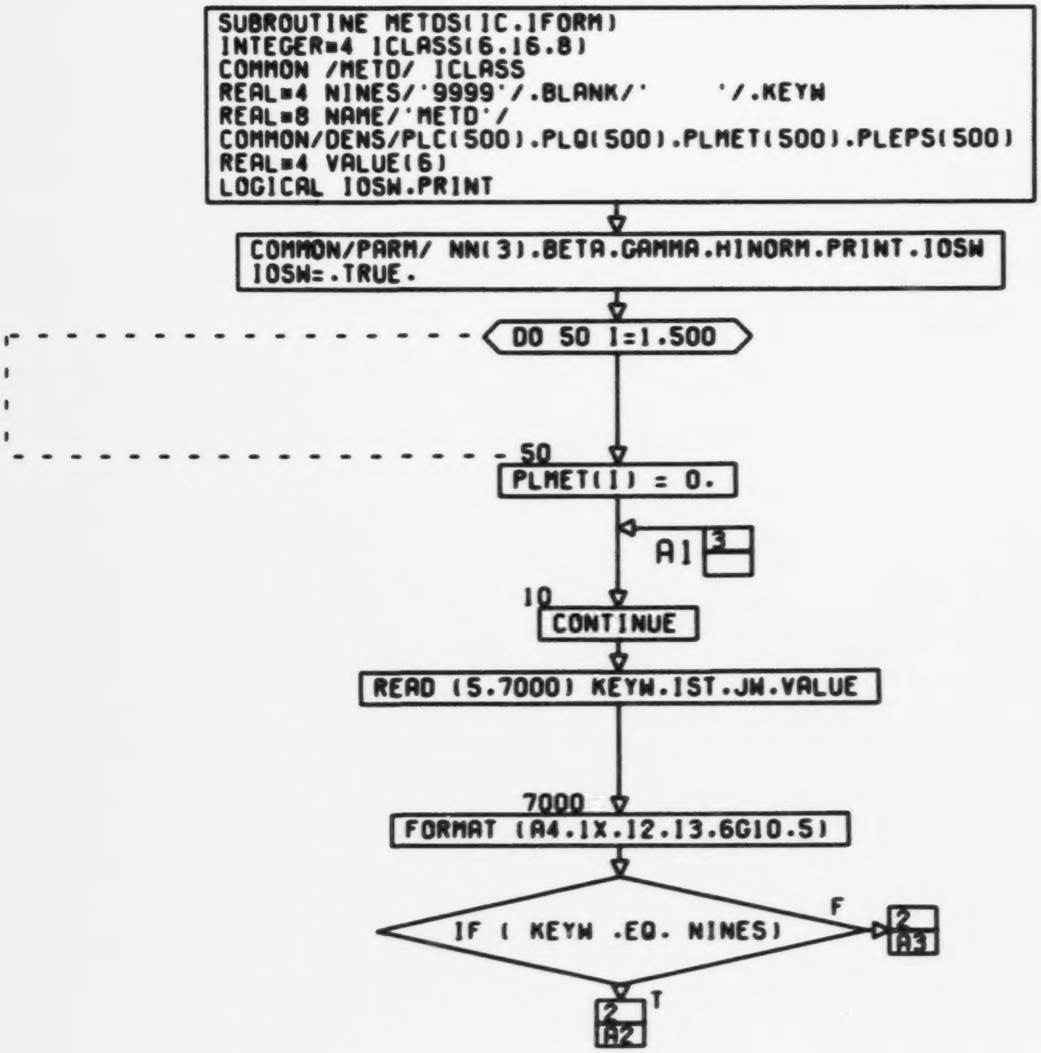

3
A4
IF (KEYW .NE. BLANK)
F
T
CALL ERRX(250.NAME)
WRITE (6.7015) DATA
7015
FORMAT(T11.6(G10.4.10X))
DO 350 I=1.6
LIMIT(NOX.1)=DATA(I)
NOX=NOX+1
IF(NOX .GT. NO)
F
T
GO TO 360
5
A5
350
CONTINUE
GO TO 210
3
A3


C CALCULATE CENTER VALUE FOR EACH CLASS
4
3
3
A5
360
DO 375 I=1.NO
LOWLIM=LIMIT(I.II)
IF (I .EQ. NO)
F
T
HILIM=LIMIT(NO.II) + HINORM
IF(I.NE.NO)
F
T
HILIM= LIMIT(I+1.II)
CENTER(I.II)= (LOWLIM+HILIM)/2.
375
CONTINUE

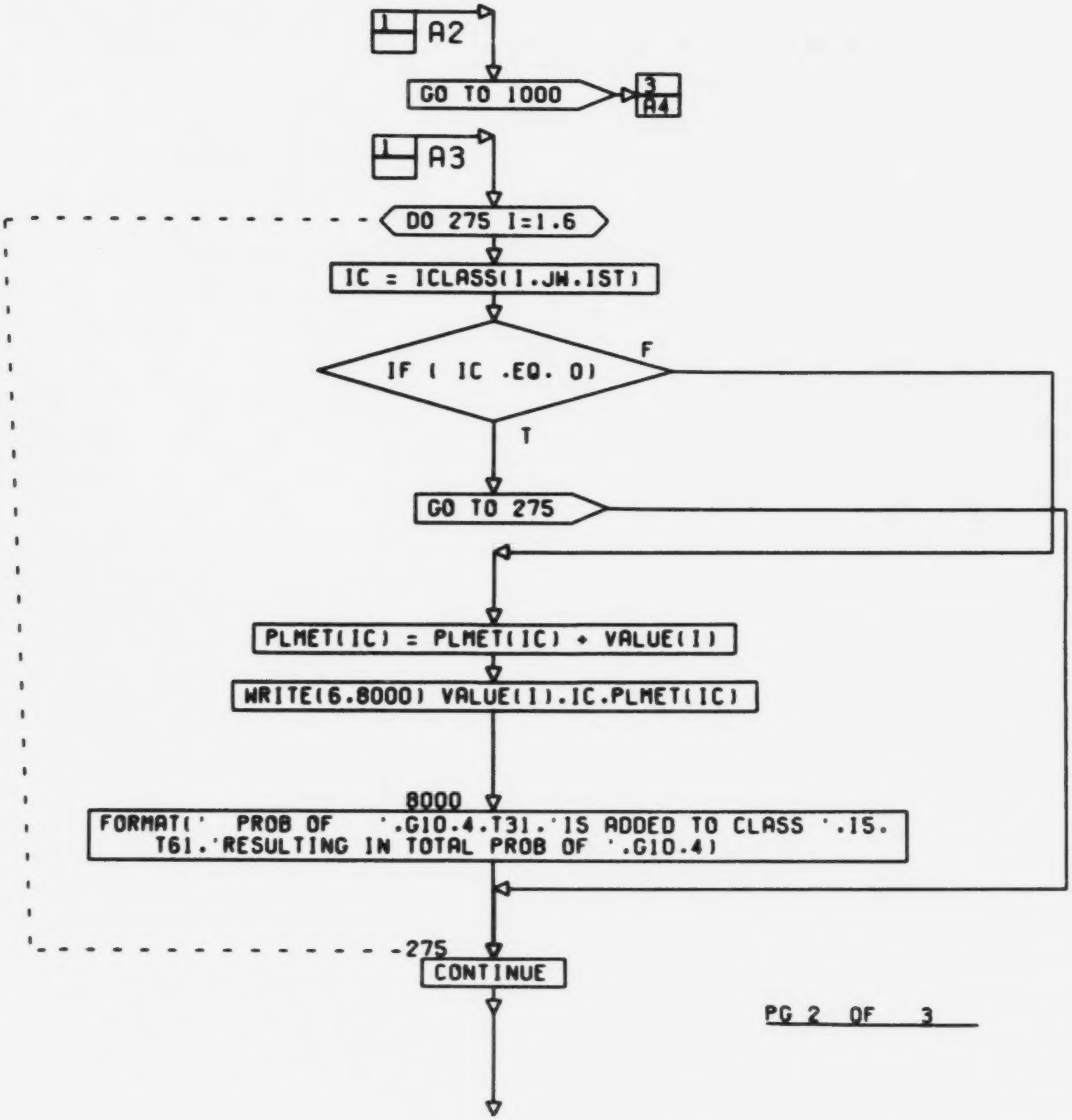
PG 5 OF 6


IF (KEYW .EQ. NINES)
F
T
GO TO 1000
GO TO 10
1
A1
2
A6
1000
RETURN
END

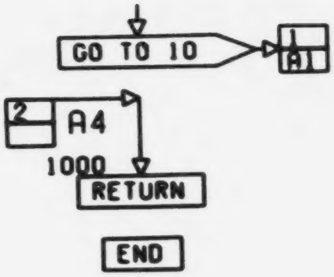
PG 6 FINAL



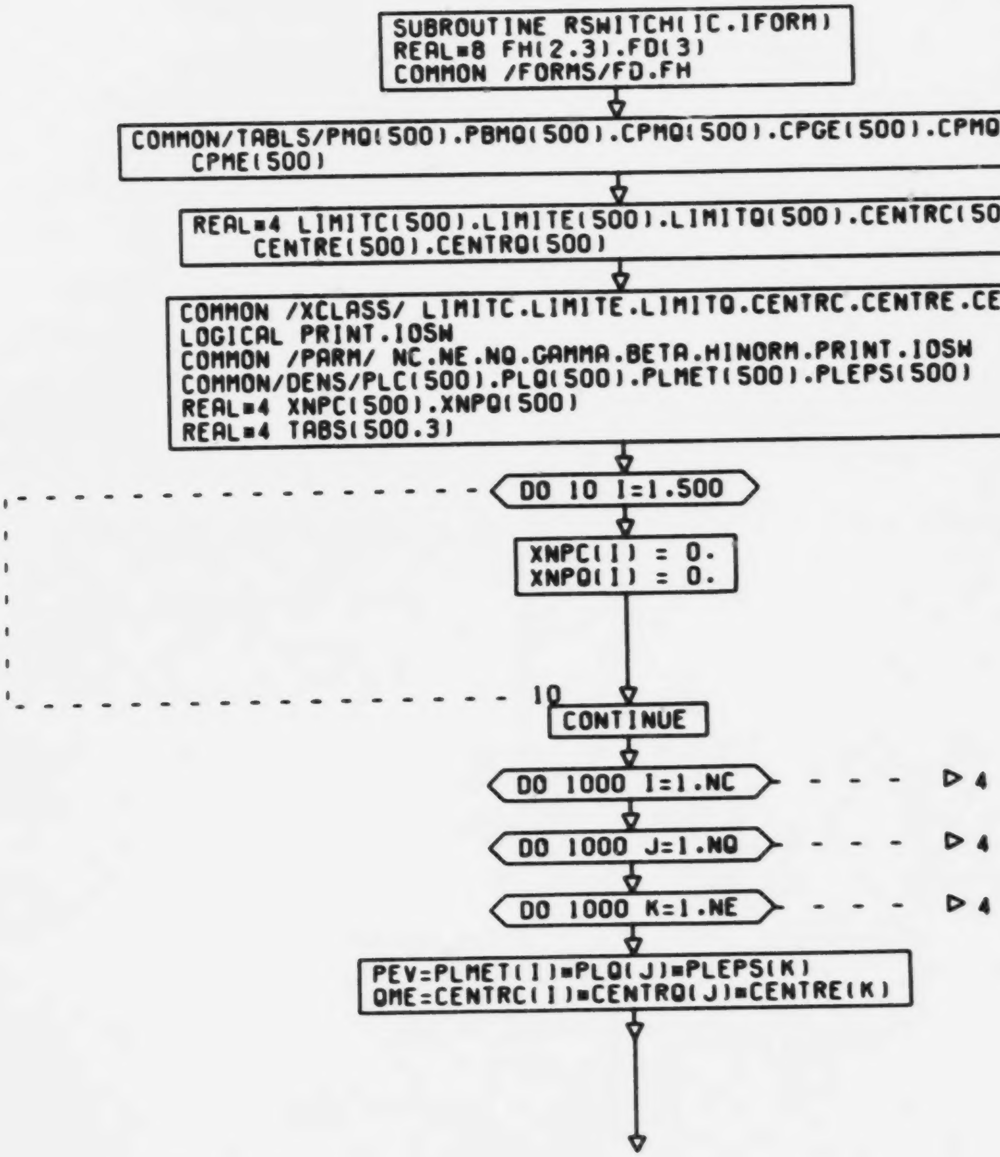
```
SUBROUTINE METDS(IC.IFORM)
INTEGER*4 ICLASS(6.16.8)
COMMON /METD/ ICLASS
REAL*4 NINES/'9999'/.BLANK/'    '/.KEYW
REAL*8 NAME/'METD'/
COMMON/DENS/PLC(500).PLQ(500).PLMET(500).PLEPS(500)
REAL*4 VALUE(6)
LOGICAL IOSW.PRINT

COMMON/PARM/ NN(3).BETA.GAMMA.HINORM.PRINT.IOSW
IOSW=.TRUE.

DO 50 I=1.500
50 PLMET(I) = 0.
10 CONTINUE
READ (5.7000) KEYW.IST.JW.VALUE
7000 FORMAT (A4.1X.I2.I3.6G10.5)
IF ( KEYW .EQ. NINES)
```


1
A2
GO TO 1000
3
A4
1
A3
DO 275 I=1.6
IC = ICLASS(I.JW.IST)
IF (IC .EQ. 0)
F
T
GO TO 275
PLMET(IC) = PLMET(IC) + VALUE(I)
WRITE(6.8000) VALUE(I).IC.PLMET(IC)
8000
FORMAT(' PROB OF '.G10.4.T31.'IS ADDED TO CLASS '.I5.
T61.'RESULTING IN TOTAL PROB OF '.G10.4)
275
CONTINUE

PG 2 OF 3

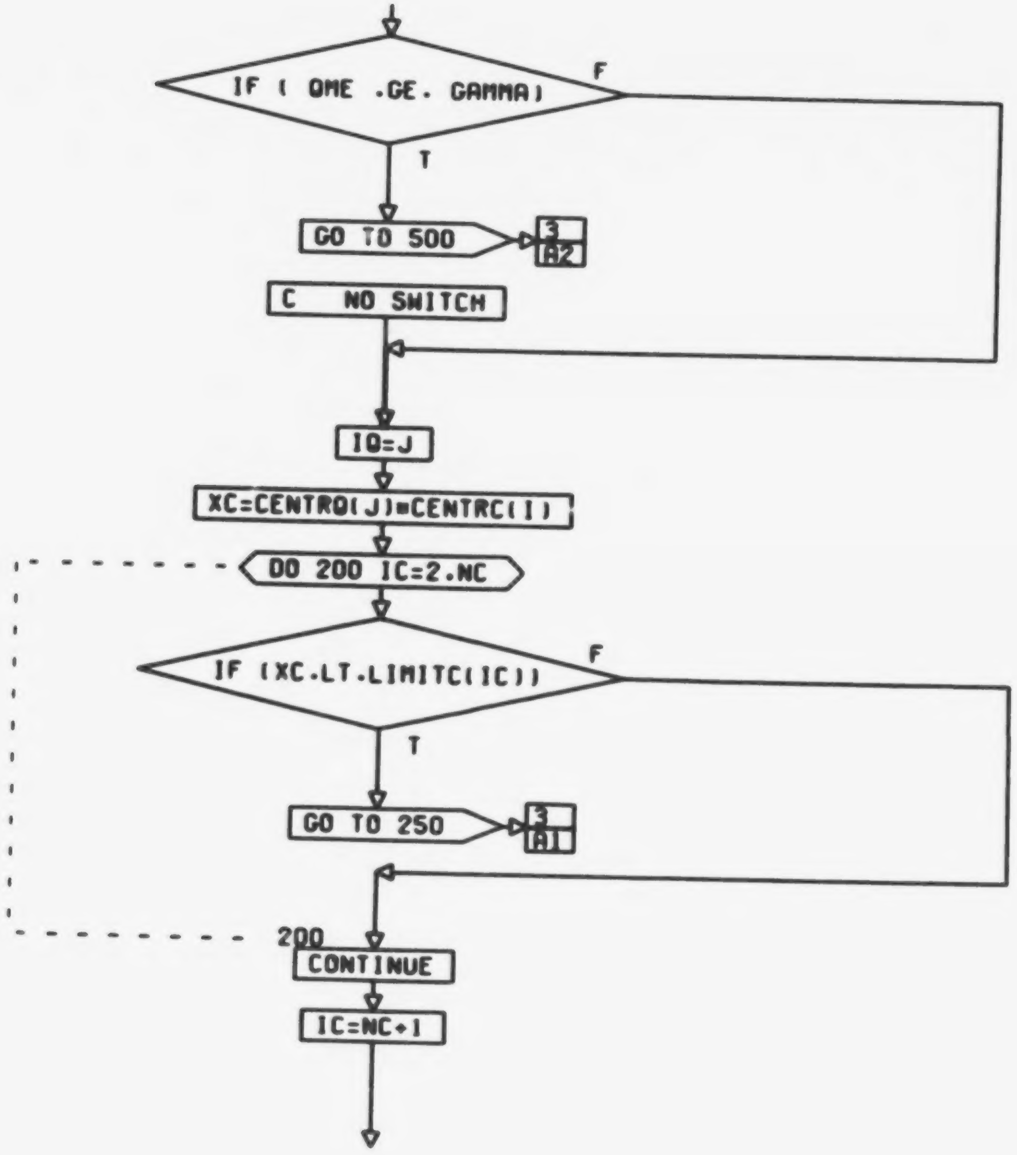

GO TO 10
1
A1
2
A4
1000
RETURN
END

PG 3 FINAL

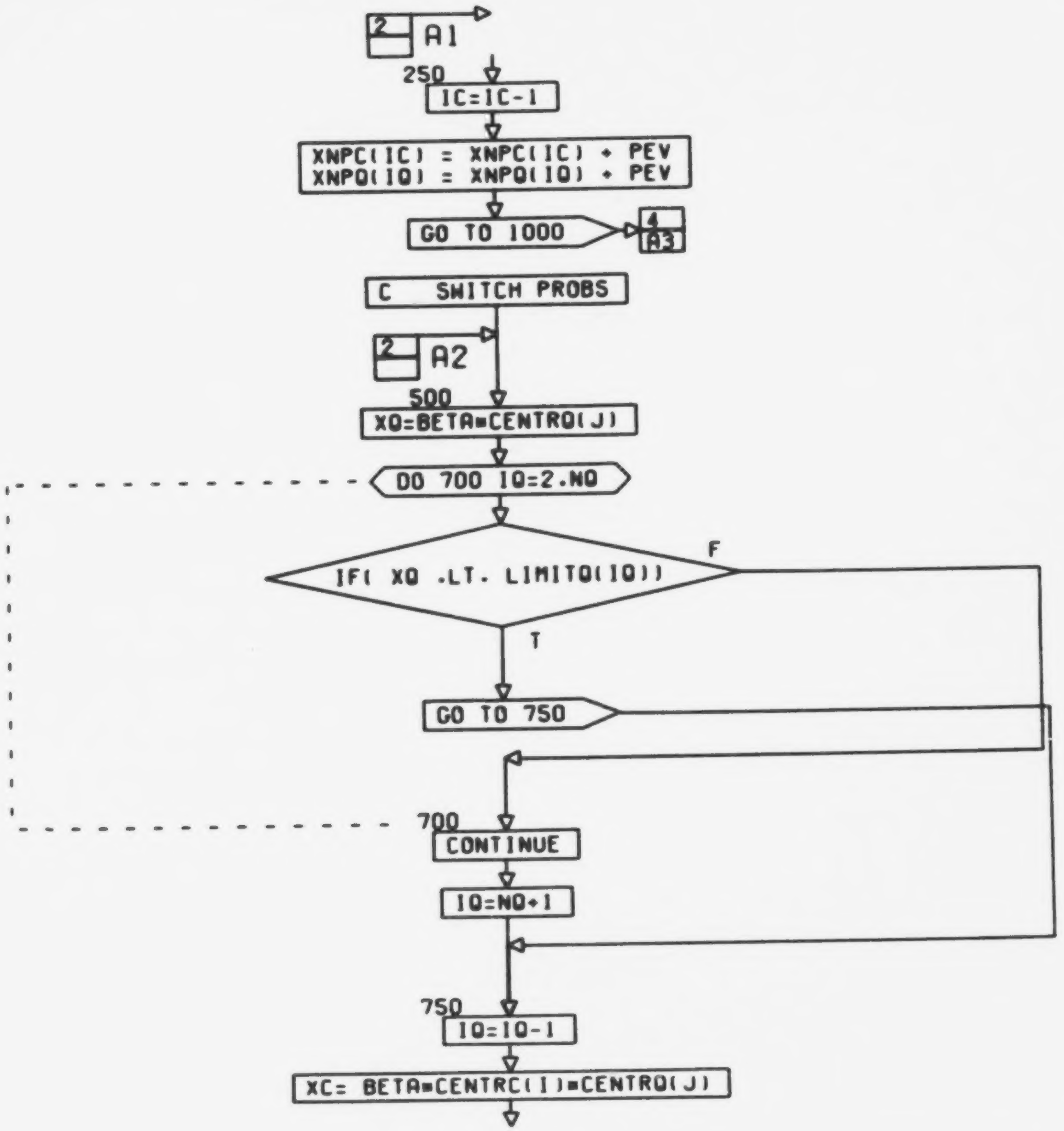


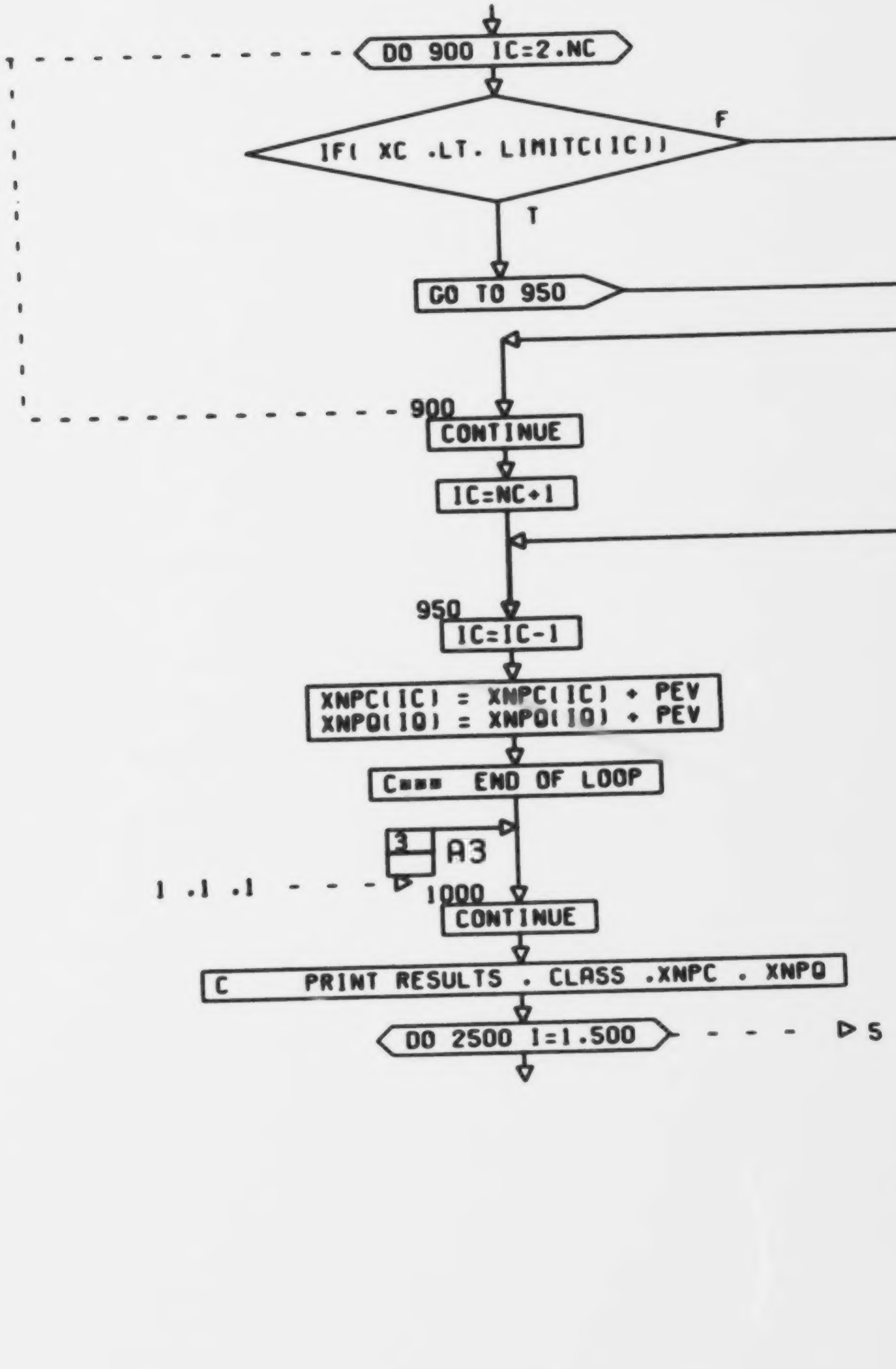
```
SUBROUTINE RSWITCH(IC.IFORM)
REAL*8 FH(2.3).FD(3)
COMMON /FORMS/FD.FH
COMMON/TABLS/PMQ(500).PBMQ(500).CPMQ(500).CPGE(500).CPMQE(500).
     CPME(500)
REAL*4 LIMITC(500).LIMITE(500).LIMITQ(500).CENTRC(500).
     CENTRE(500).CENTRQ(500)
COMMON /XCLASS/ LIMITC.LIMITE.LIMITQ.CENTRC.CENTRE.CENTRQ
LOGICAL PRINT.IOSW
COMMON /PARM/ NC.NE.NQ.GAMMA.BETA.MINORM.PRINT.IOSW
COMMON/DENS/PLC(500).PLQ(500).PLMET(500).PLEPS(500)
REAL*4 XNPC(500).XNPQ(500)
REAL*4 TABS(500.3)
DO 10 I=1.500
XNPC(I) = 0.
XNPQ(I) = 0.
10 CONTINUE
DO 1000 I=1.NC
DO 1000 J=1.NQ
DO 1000 K=1.NE
PEV=PLMET(I)*PLQ(J)*PLEPS(K)
QME=CENTRC(I)*CENTRQ(J)*CENTRE(K)
```

PG 1 OF 7

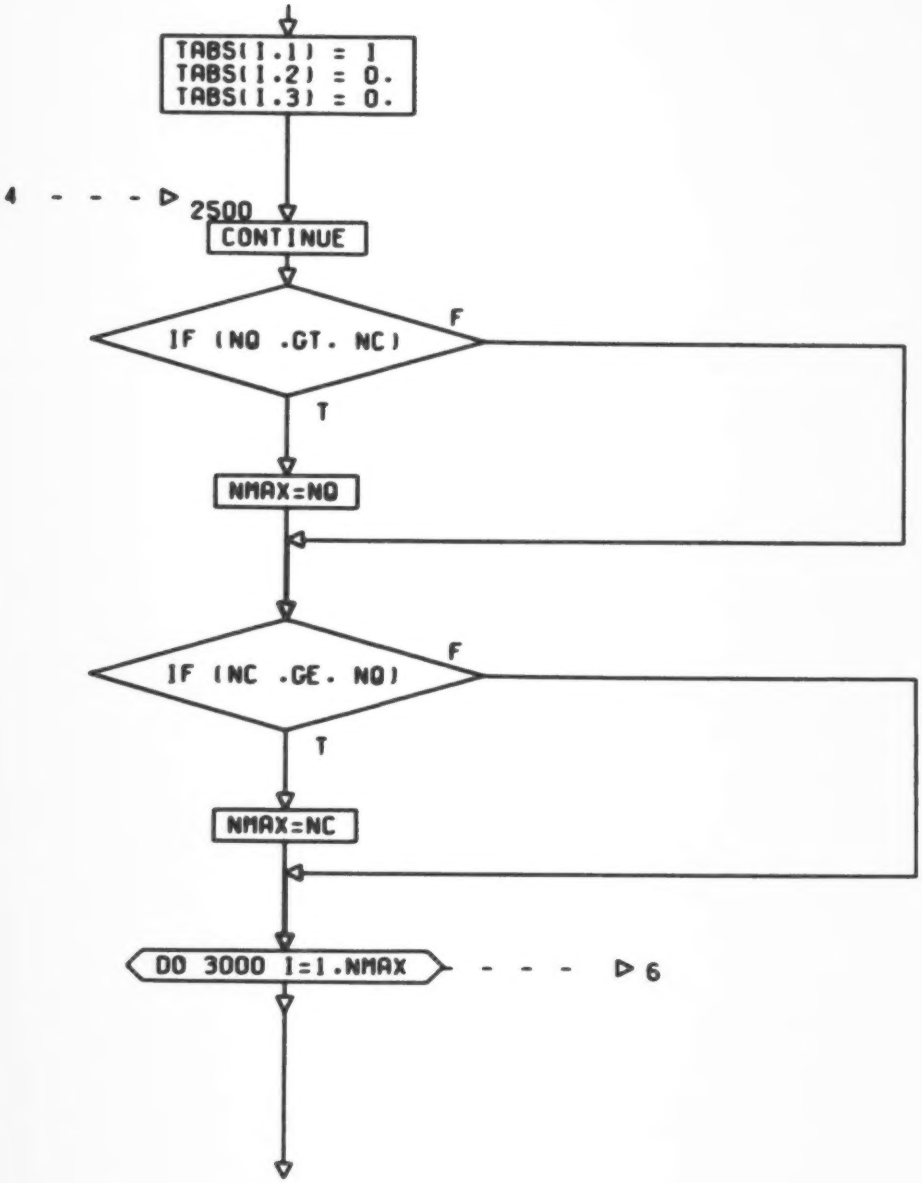

IF (OME .GE. GAMMA)
F
T
GO TO 500
3
A2
C NO SWITCH
IO=J
XC=CENTRO(J)-CENTRC(I)
DO 200 IC=2,NC
IF (XC.LT.LIMITC(IC))
F
T
GO TO 250
3
A1
200
CONTINUE
IC=NC+1

PG 2 OF 7

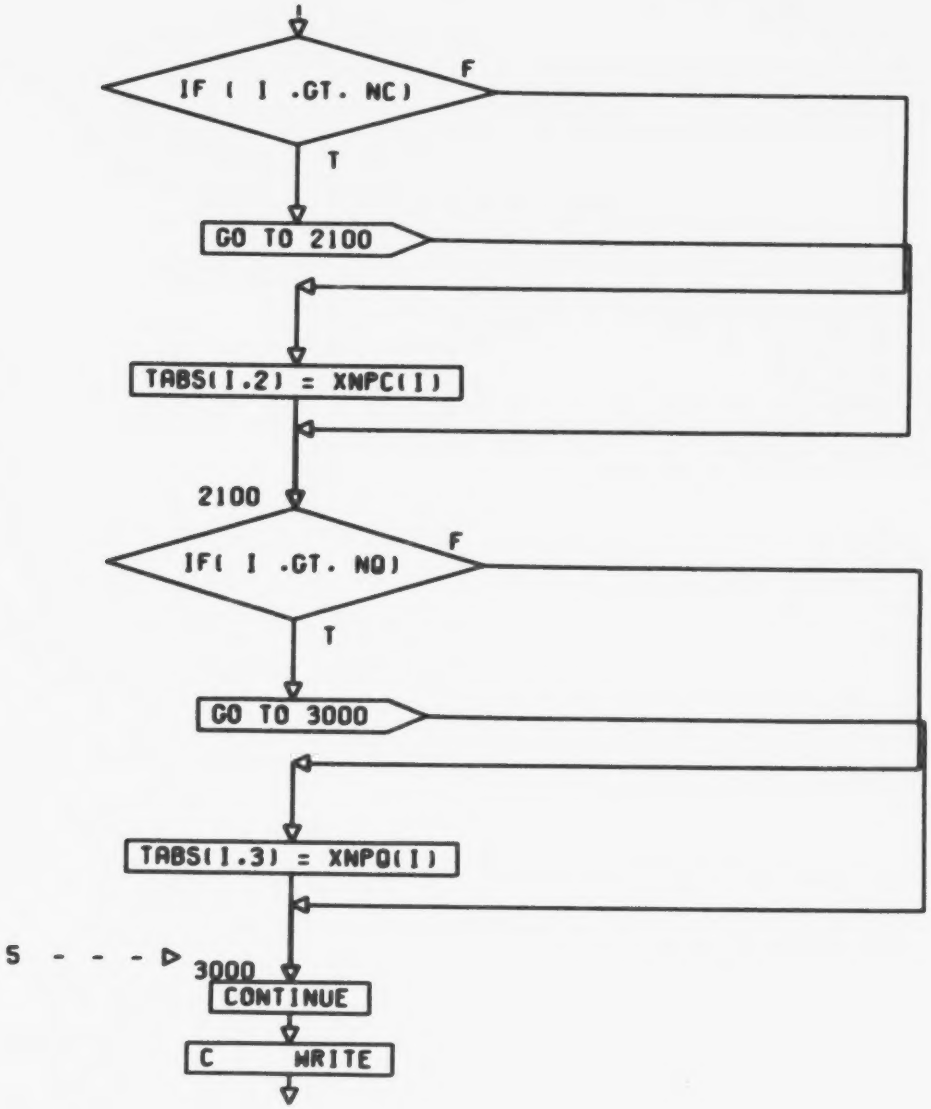

2
A1
250
IC=IC-1
XNPC(IC) = XNPC(IC) + PEV
XNPQ(IQ) = XNPQ(IQ) + PEV
GO TO 1000
4
A3
C SWITCH PROBS
2
A2
500
XQ=BETA*CENTRQ(J)
DO 700 IQ=2,NQ
IF(XQ .LT. LIMITQ(IQ))
F
T
GO TO 750
700
CONTINUE
IQ=NQ+1
750
IQ=IQ-1
XC= BETA*CENTRC(I)*CENTRQ(J)


DO 900 IC=2.NC
IF(XC .LT. LIMITC(IC))
F
T
GO TO 950
900
CONTINUE
IC=NC+1
950
IC=IC-1
XNPC(IC) = XNPC(IC) + PEV
XNPQ(IQ) = XNPQ(IQ) + PEV
C*** END OF LOOP
3
A3
1 .1 .1
1000
CONTINUE
C PRINT RESULTS . CLASS .XNPC . XNPQ
DO 2500 I=1.500
5

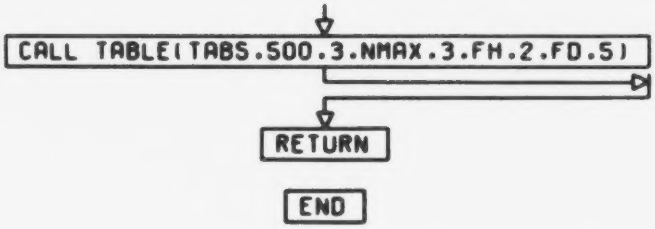
PG 4 OF 7


TABS(I,1) = 1
TABS(I,2) = 0.
TABS(I,3) = 0.
4
2500
CONTINUE
IF (NO .GT. NC)
F
T
NMAX=NO
IF (NC .GE. NO)
F
T
NMAX=NC
DO 3000 I=1,NMAX
6

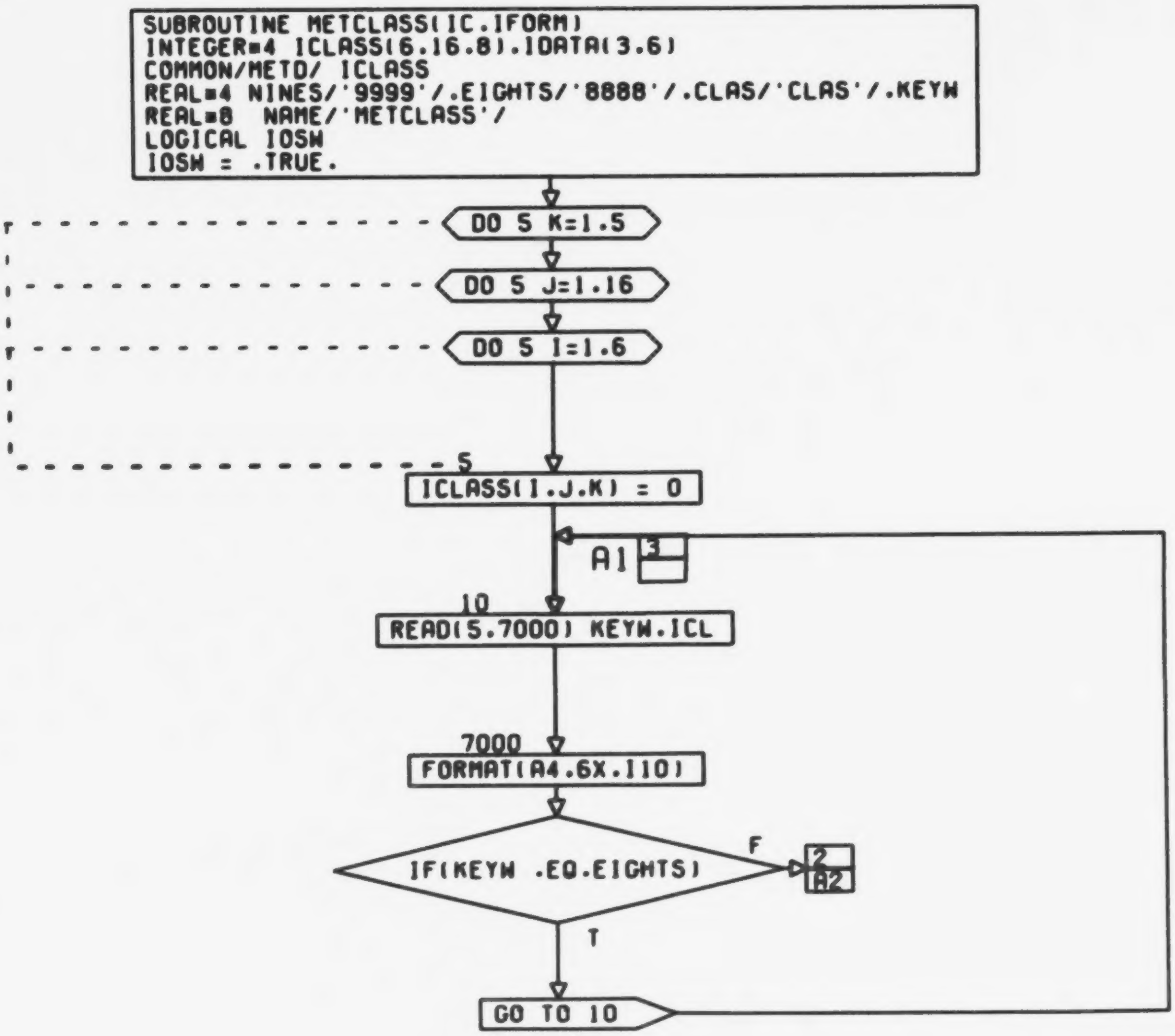
PG 5 OF 7


IF (I .GT. NC)
F
T
GO TO 2100
TABS(I.2) = XNPC(I)
2100
IF(I .GT. NO)
F
T
GO TO 3000
TABS(I.3) = XNPQ(I)
5
3000
CONTINUE
C WRITE

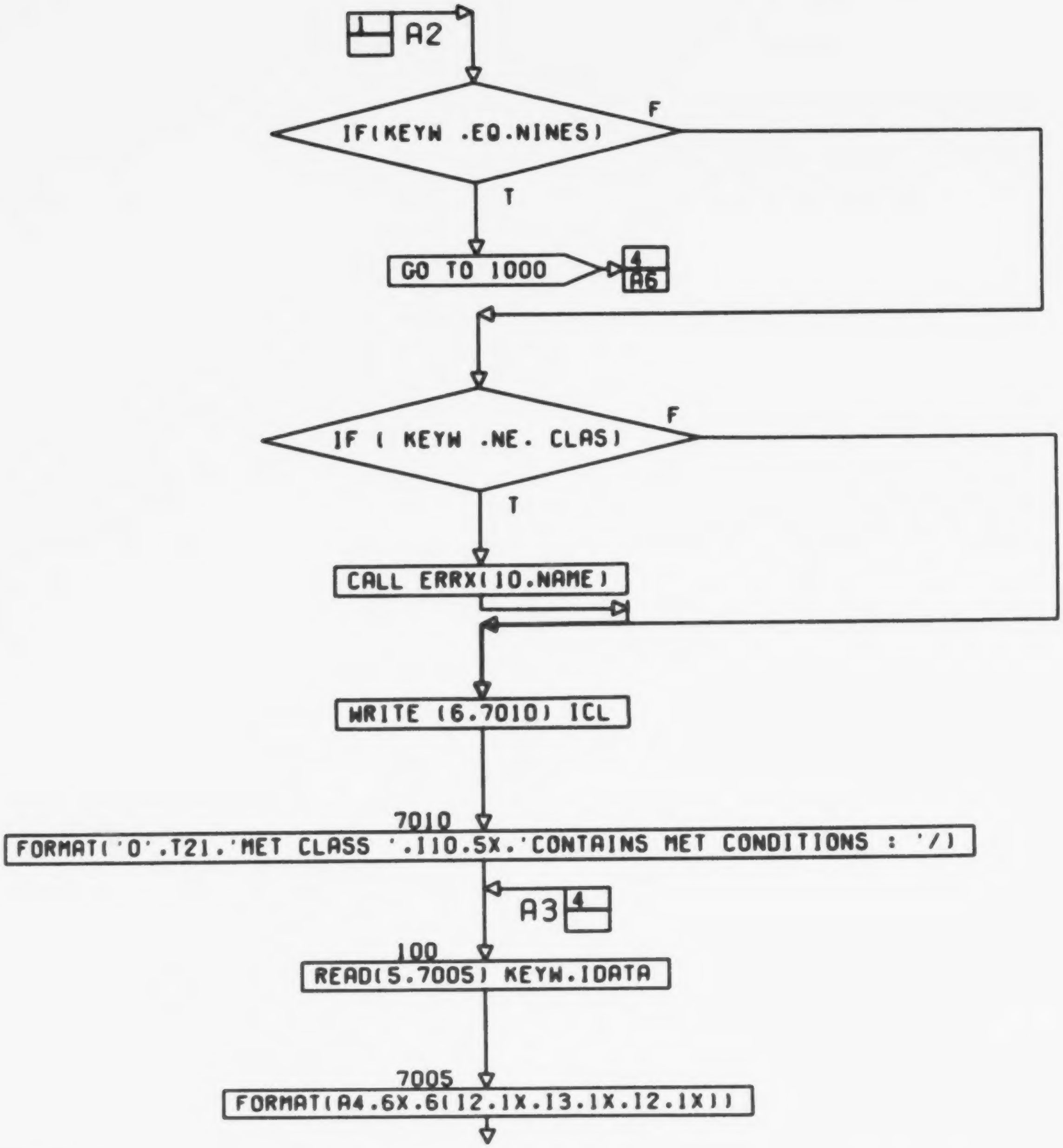
PG 6 OF 7


CALL TABLE(TABS.500.3.NMAX.3.FH.2.FD.5)
RETURN
END

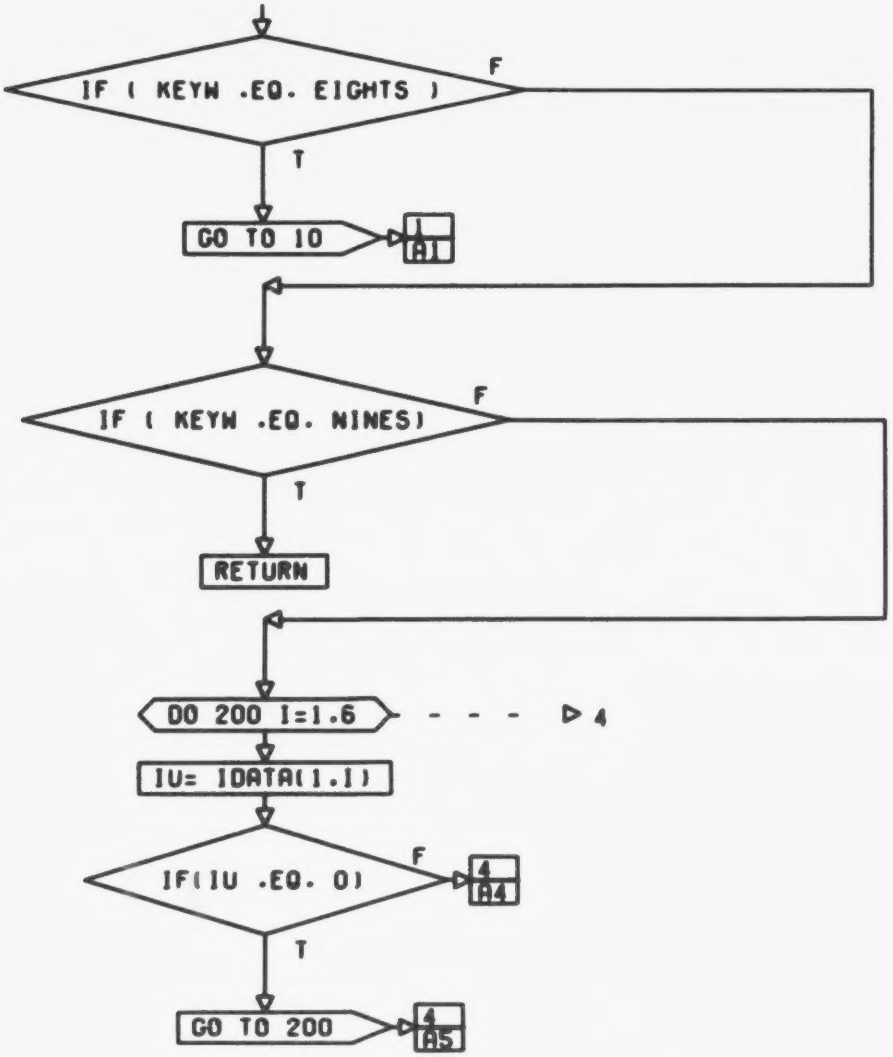
PG 7 FINAL



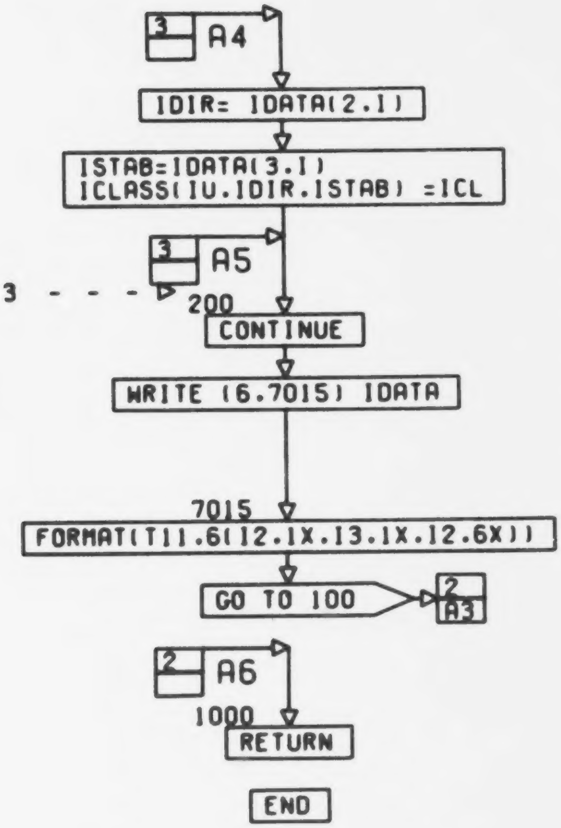
```
SUBROUTINE METCLASS(IC.IFORM)
INTEGER*4 ICLASS(6.16.8).IDATA(3.6)
COMMON/METD/ ICLASS
REAL*4 NINES/'9999'/.EIGHTS/'8888'/.CLAS/'CLAS'/.KEYW
REAL*8  NAME/'METCLASS'/
LOGICAL IOSW
IOSW = .TRUE.
DO 5 K=1.5
DO 5 J=1.16
DO 5 I=1.6
5 ICLASS(I.J.K) = 0
10 READ(5.7000) KEYW.ICL
7000 FORMAT(A4.6X.I10)
IF(KEYW .EQ.EIGHTS)
GO TO 10
```

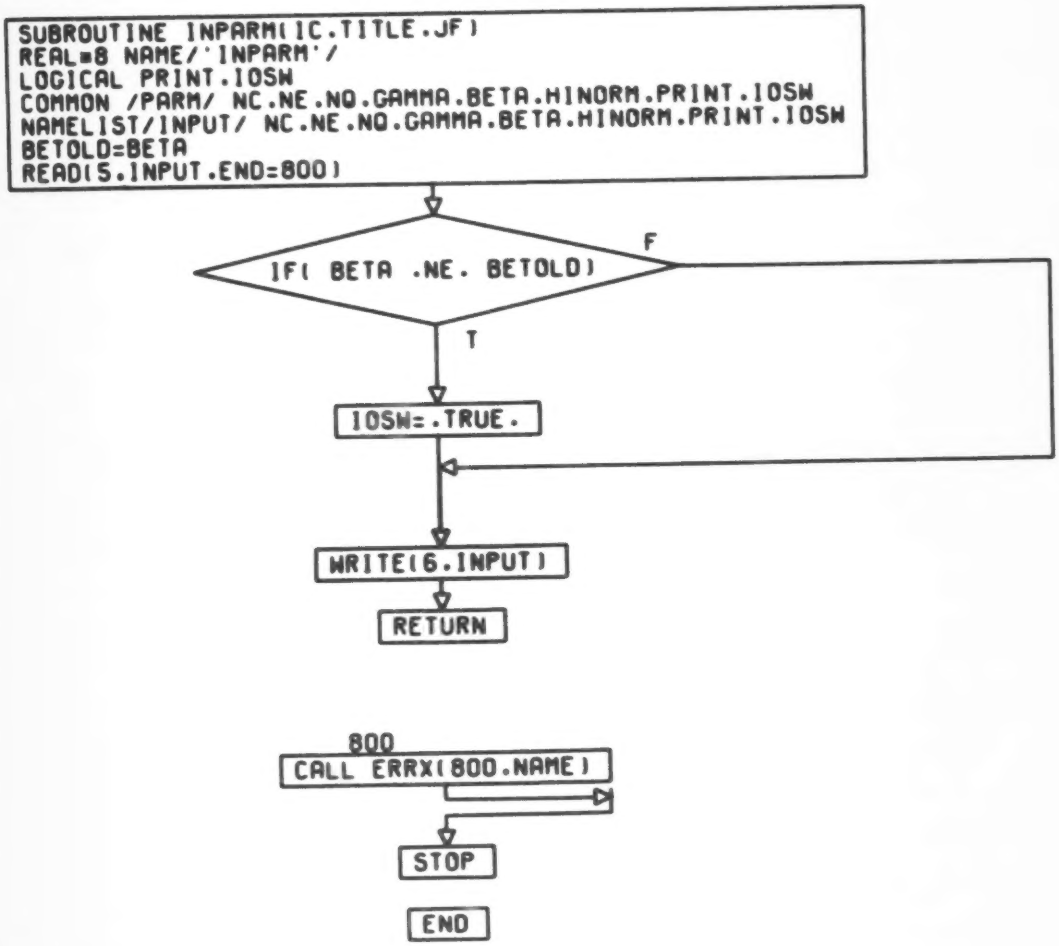

1
A2
IF(KEYW .EQ.NINES)
F
T
GO TO 1000
4
A6
IF (KEYW .NE. CLAS)
F
T
CALL ERRX(10.NAME)
WRITE (6.7010) ICL
7010
FORMAT('O'.T21.'MET CLASS '.I10.5X.'CONTAINS MET CONDITIONS : '/)
A3
4
100
READ(5.7005) KEYW.IDATA
7005
FORMAT(A4.6X.6(I2.1X.I3.1X.I2.1X))

PG 2 OF 4

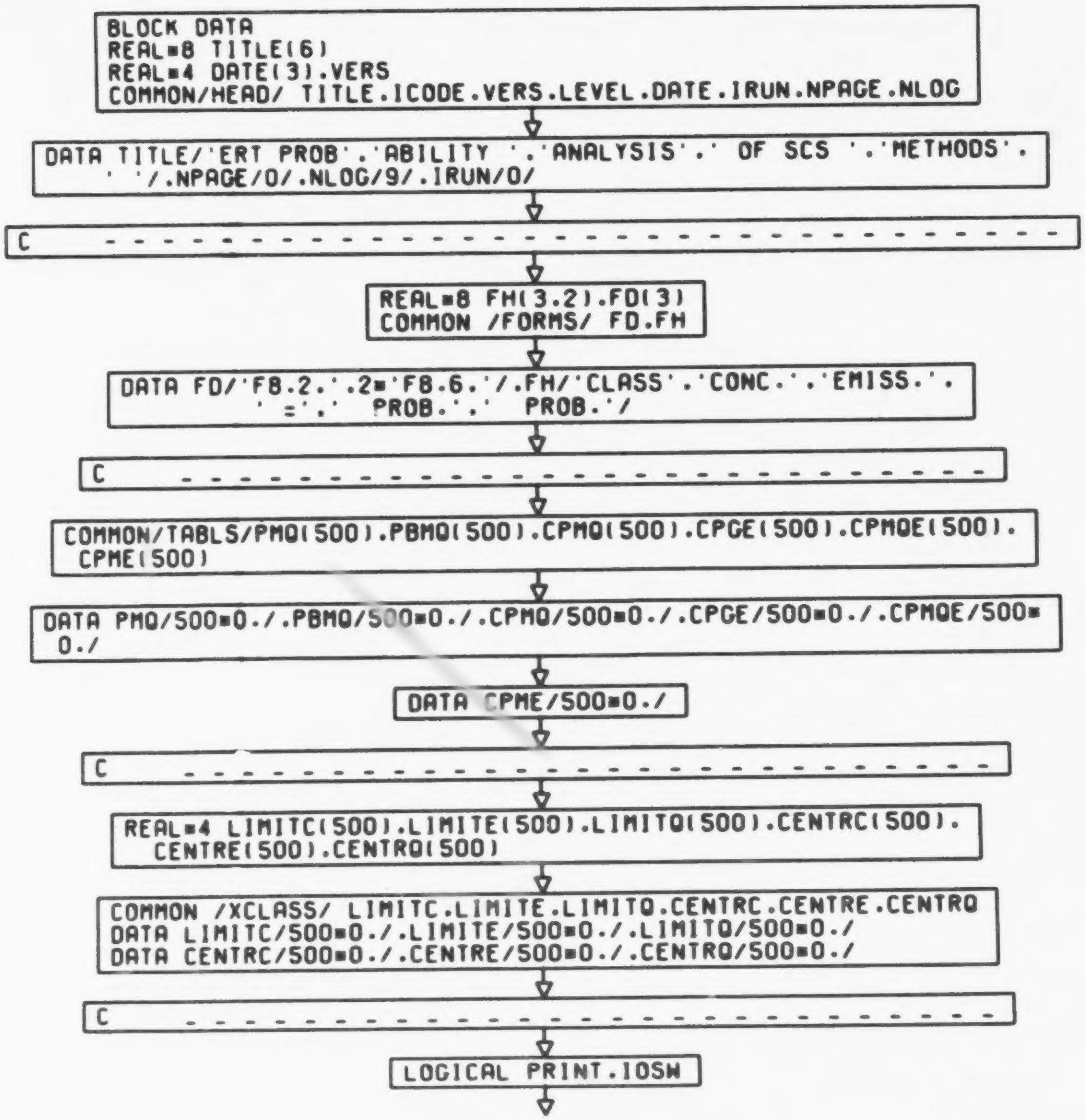

IF (KEYW .EQ. EIGHTS)
F
T
GO TO 10
1
A1
IF (KEYW .EQ. NINES)
F
T
RETURN
DO 200 I=1,6
4
IU= IDATA(1,I)
IF(IU .EQ. 0)
F
4
A4
T
GO TO 200
4
A5

PG 3 OF 4


3
A4
IDIR= IDATA(2.I)
ISTAB=IDATA(3.I)
ICLASS(IU.IDIR.ISTAB) =ICL
3
A5
3
200
CONTINUE
WRITE (6.7015) IDATA
7015
FORMAT(T11.6(I2.1X.I3.1X.I2.6X))
GO TO 100
2
A3
2
A6
1000
RETURN
END

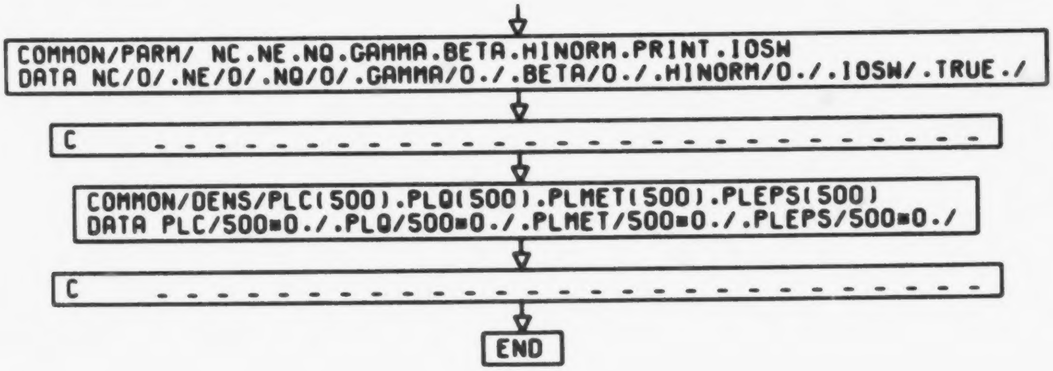


```
SUBROUTINE INPARM(IC.TITLE.JF)
REAL*8 NAME/'INPARM'/
LOGICAL PRINT.IOSW
COMMON /PARM/ NC.NE.NO.GAMMA.BETA.HINORM.PRINT.IOSW
NAMELIST/INPUT/ NC.NE.NO.GAMMA.BETA.HINORM.PRINT.IOSW
BETOLD=BETA
READ(5.INPUT.END=800)
IF( BETA .NE. BETOLD)
IOSW=.TRUE.
WRITE(6.INPUT)
RETURN
800 CALL ERRX(800.NAME)
STOP
END
```



```
BLOCK DATA
REAL*8 TITLE(6)
REAL*4 DATE(3).VERS
COMMON/HEAD/ TITLE.ICODE.VERS.LEVEL.DATE.IRUN.NPAGE.NLOG
DATA TITLE/'ERT PROB'.'ABILITY '.'ANALYSIS'.' OF SCS '.'METHODS'.
     ' '/.NPAGE/0/.NLOG/9/.IRUN/0/
C    - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
REAL*8 FH(3.2).FD(3)
COMMON /FORMS/ FD.FH
DATA FD/'F8.2.'.2*'F8.6.'/.FH/'CLASS'.'CONC.'.'EMISS.'.
            ' ='.'  PROB.'.'  PROB.'/
C    - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
COMMON/TABLS/PMQ(500).PBMQ(500).CPMQ(500).CPGE(500).CPMQE(500).
 CPME(500)
DATA PMQ/500*0./.PBMQ/500*0./.CPMQ/500*0./.CPGE/500*0./.CPMQE/500*
 0./
DATA CPME/500*0./
C    - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
REAL*4 LIMITC(500).LIMITE(500).LIMITQ(500).CENTRC(500).
  CENTRE(500).CENTRQ(500)
COMMON /XCLASS/ LIMITC.LIMITE.LIMITQ.CENTRC.CENTRE.CENTRQ
DATA LIMITC/500*0./.LIMITE/500*0./.LIMITQ/500*0./
DATA CENTRC/500*0./.CENTRE/500*0./.CENTRQ/500*0./
C    - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
LOGICAL PRINT.IOSW
```

PG 1 OF 2



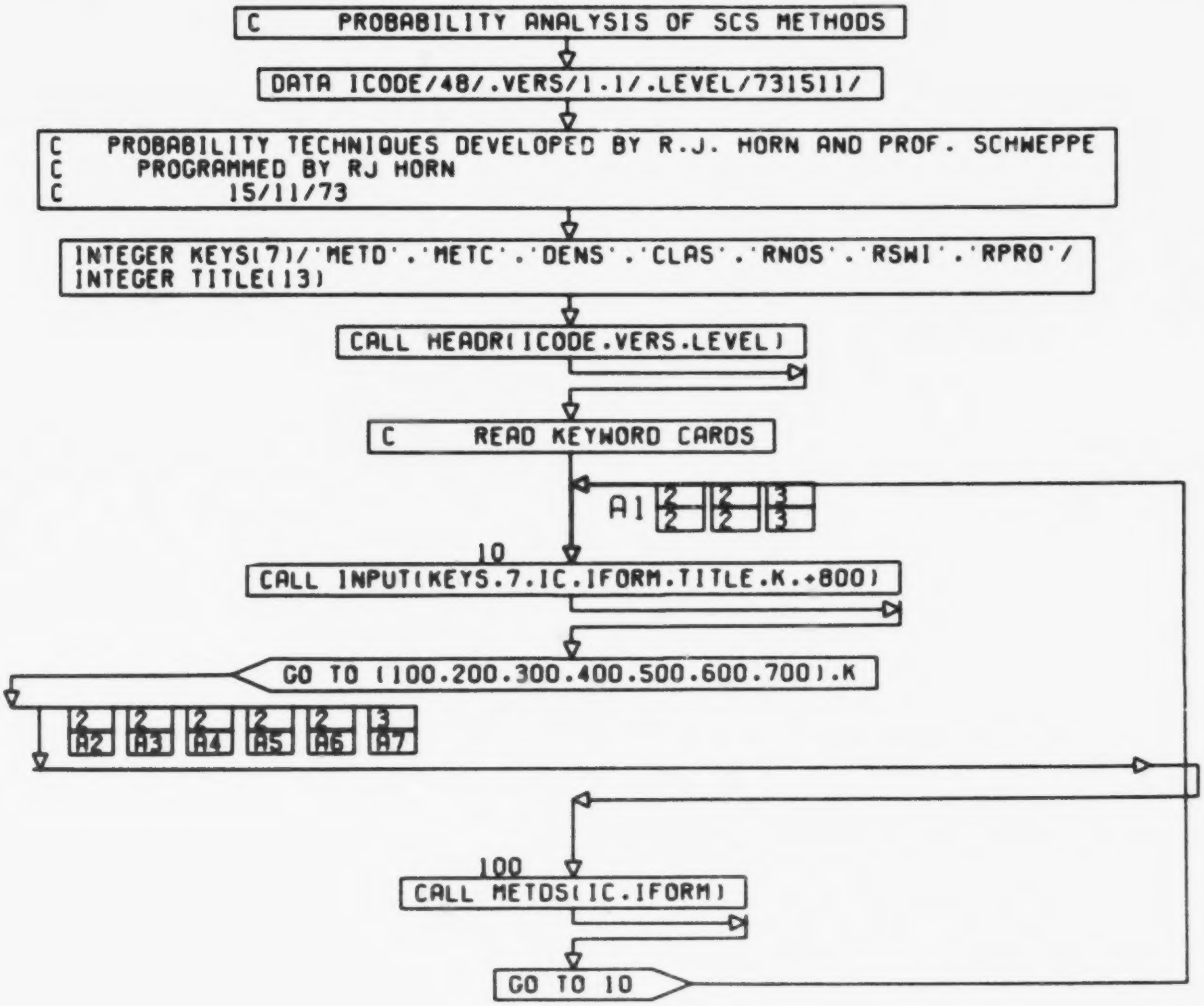
```
COMMON/PARM/ NC.NE.NQ.GAMMA.BETA.HINORM.PRINT.IOSW
DATA NC/0/.NE/0/.NQ/0/.GAMMA/0./.BETA/0./.HINORM/0./.IOSW/.TRUE./
```

```
C     - - - - - - - - - - - - - - - - - - - - - - - - - - -
```

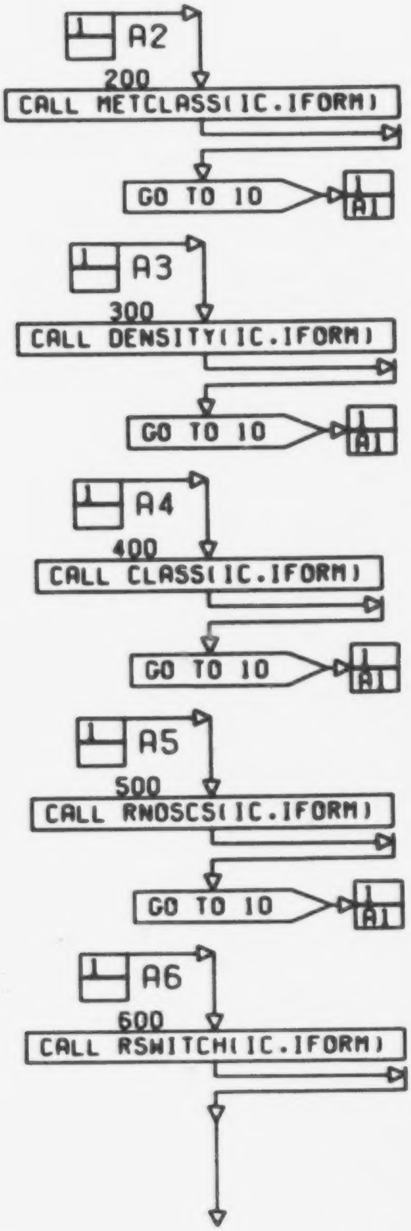
```
COMMON/DENS/PLC(500).PLQ(500).PLMET(500).PLEPS(500)
DATA PLC/500*0./.PLQ/500*0./.PLMET/500*0./.PLEPS/500*0./
```

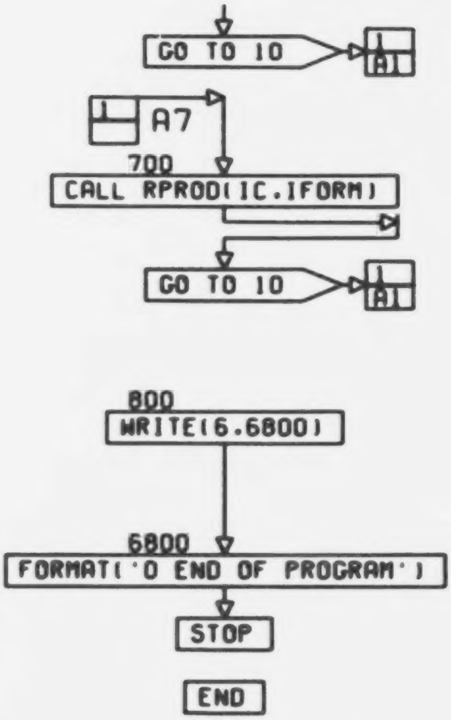
```
C     - - - - - - - - - - - - - - - - - - - - - - - - - - -
```

PG 2   FINAL

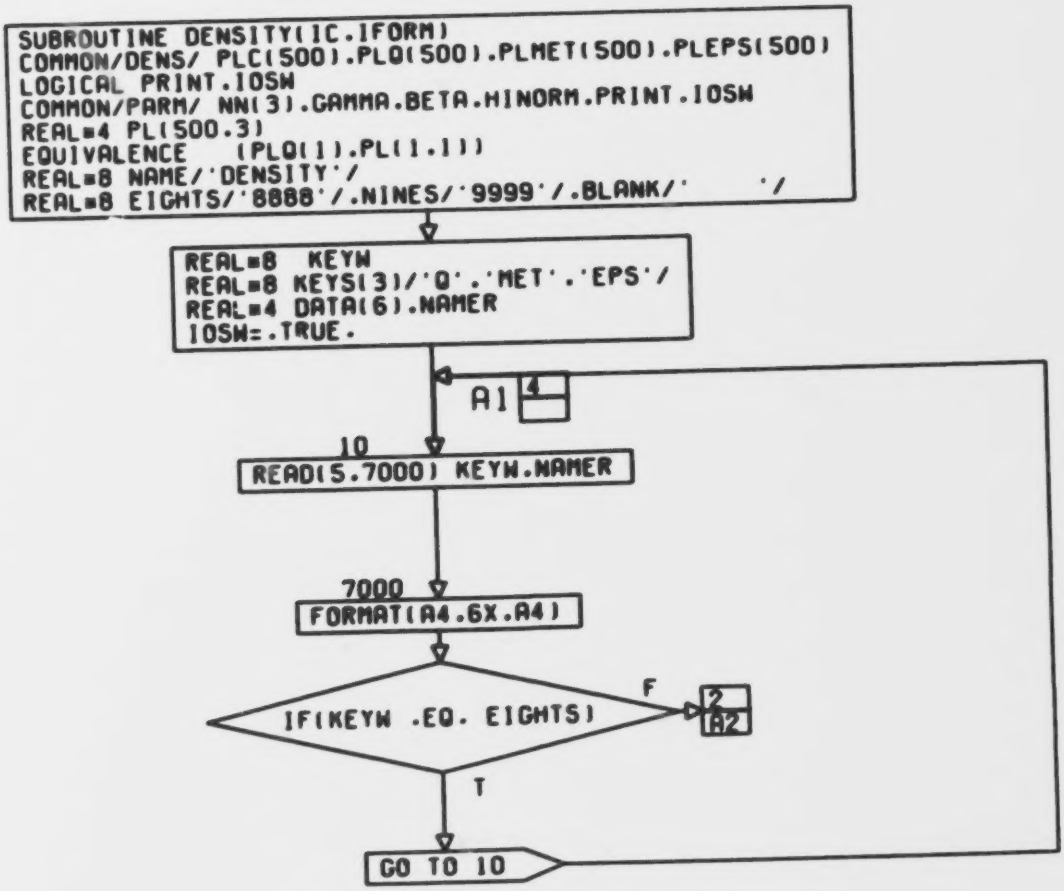


```
C     PROBABILITY ANALYSIS OF SCS METHODS
DATA ICODE/48/.VERS/1.1/.LEVEL/731511/
C   PROBABILITY TECHNIQUES DEVELOPED BY R.J. HORN AND PROF. SCHWEPPE
C      PROGRAMMED BY RJ HORN
C            15/11/73
INTEGER KEYS(7)/'METD'.'METC'.'DENS'.'CLAS'.'RNOS'.'RSWI'.'RPRO'/
INTEGER TITLE(13)
CALL HEADR(ICODE.VERS.LEVEL)
C     READ KEYWORD CARDS
10 CALL INPUT(KEYS.7.IC.IFORM.TITLE.K.+800)
GO TO (100.200.300.400.500.600.700).K
100 CALL METDS(IC.IFORM)
GO TO 10
```

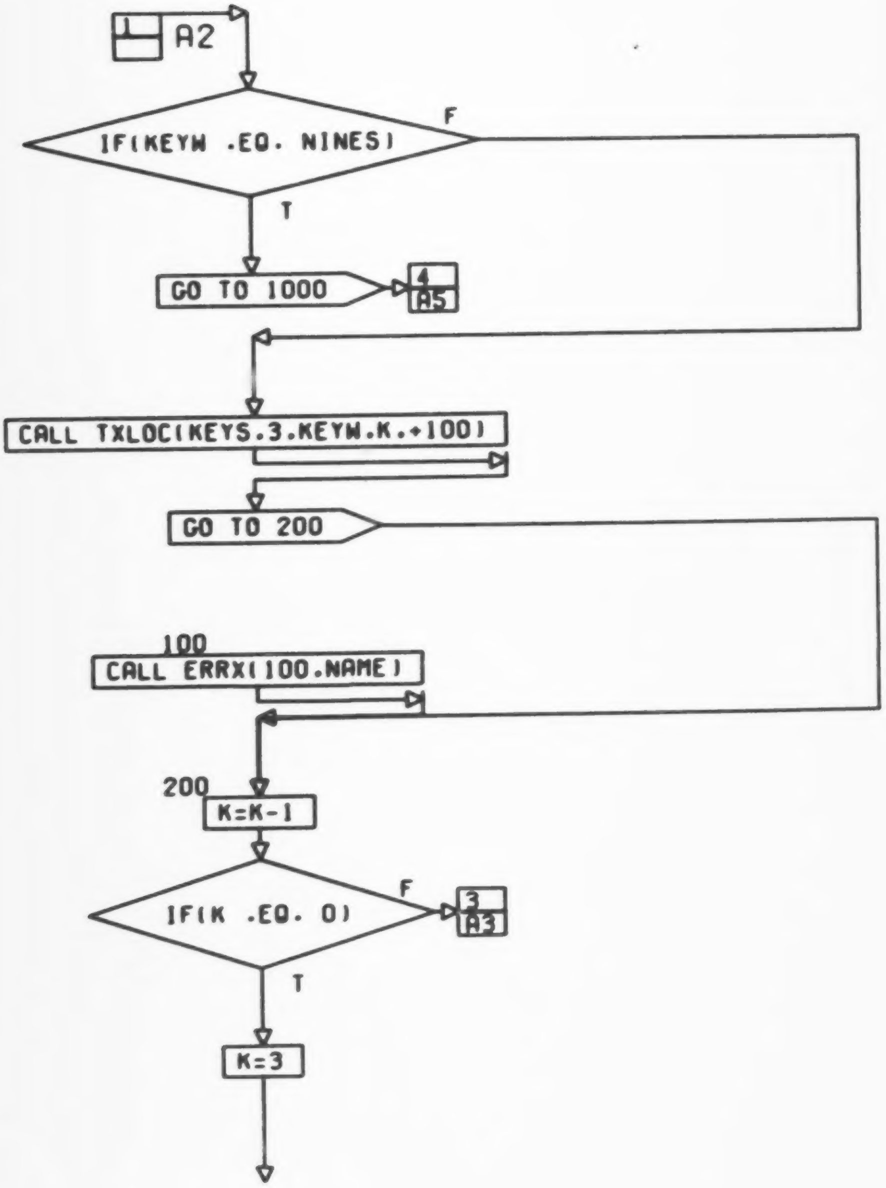

A2
200
CALL METCLASS(IC.IFORM)
GO TO 10
A1
A3
300
CALL DENSITY(IC.IFORM)
GO TO 10
A1
A4
400
CALL CLASS(IC.IFORM)
GO TO 10
A1
A5
500
CALL RNOSCS(IC.IFORM)
GO TO 10
A1
A6
600
CALL RSWITCH(IC.IFORM)


GO TO 10
A1
A7
700
CALL RPROD(IC.IFORM)
GO TO 10
A1
800
WRITE(6.6800)
6800
FORMAT('0 END OF PROGRAM')
STOP
END

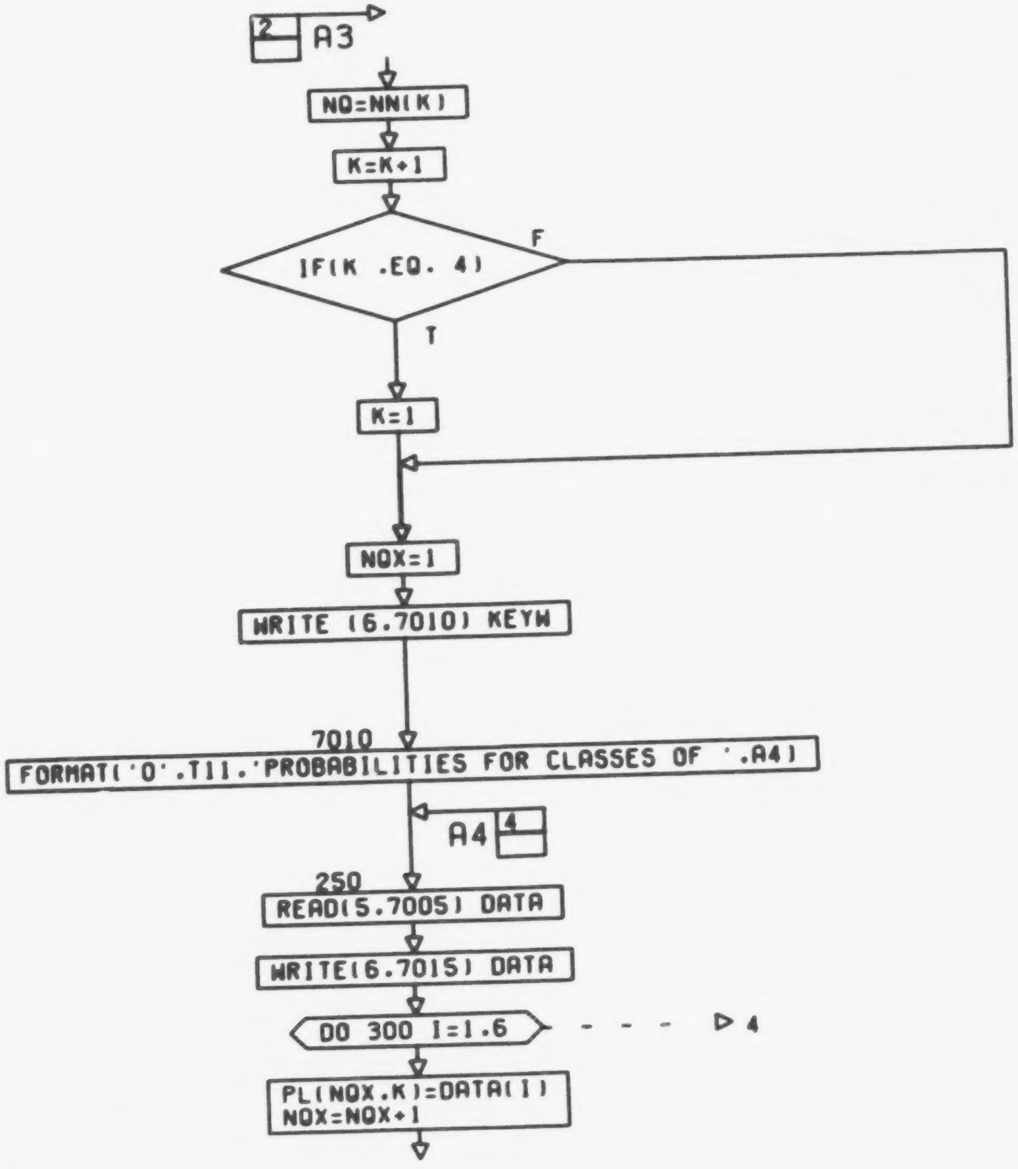
PG 3 FINAL



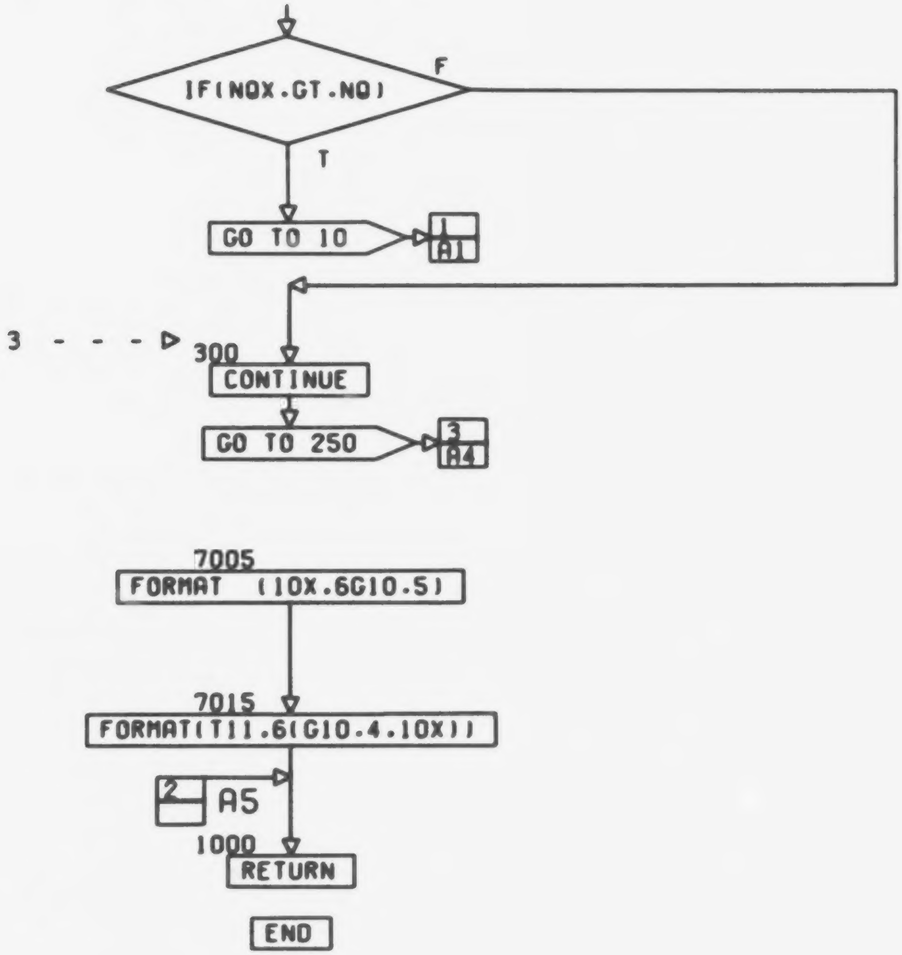
```
SUBROUTINE DENSITY(IC.IFORM)
COMMON/DENS/ PLC(500).PLQ(500).PLMET(500).PLEPS(500)
LOGICAL PRINT.IOSW
COMMON/PARM/ NN(3).GAMMA.BETA.MINORM.PRINT.IOSW
REAL*4 PL(500.3)
EQUIVALENCE   (PLQ(1).PL(1.1))
REAL*8 NAME/'DENSITY'/
REAL*8 EIGHTS/'8888'/.NINES/'9999'/.BLANK/'    '/

REAL*8  KEYW
REAL*8 KEYS(3)/'Q'.'MET'.'EPS'/
REAL*4 DATA(6).NAMER
IOSW=.TRUE.

10
READ(5.7000) KEYW.NAMER

7000
FORMAT(A4.6X.A4)

IF(KEYW .EQ. EIGHTS)

GO TO 10
```


1
A2
IF(KEYW .EQ. NINES)
F
T
GO TO 1000
4
A5
CALL TXLOC(KEYS.3.KEYW.K.+100)
GO TO 200
100
CALL ERRX(100.NAME)
200
K=K-1
IF(K .EQ. 0)
F
3
A3
T
K=3

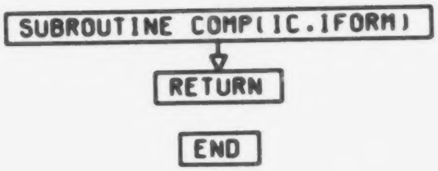
PG 2 OF 4


2
A3
NO=NN(K)
K=K+1
IF(K .EQ. 4)
F
T
K=1
NOX=1
WRITE (6.7010) KEYW
7010
FORMAT('0'.T11.'PROBABILITIES FOR CLASSES OF '.A4)
A4
4
250
READ(5.7005) DATA
WRITE(6.7015) DATA
DO 300 I=1.6
4
PL(NOX.K)=DATA(I)
NOX=NOX+1

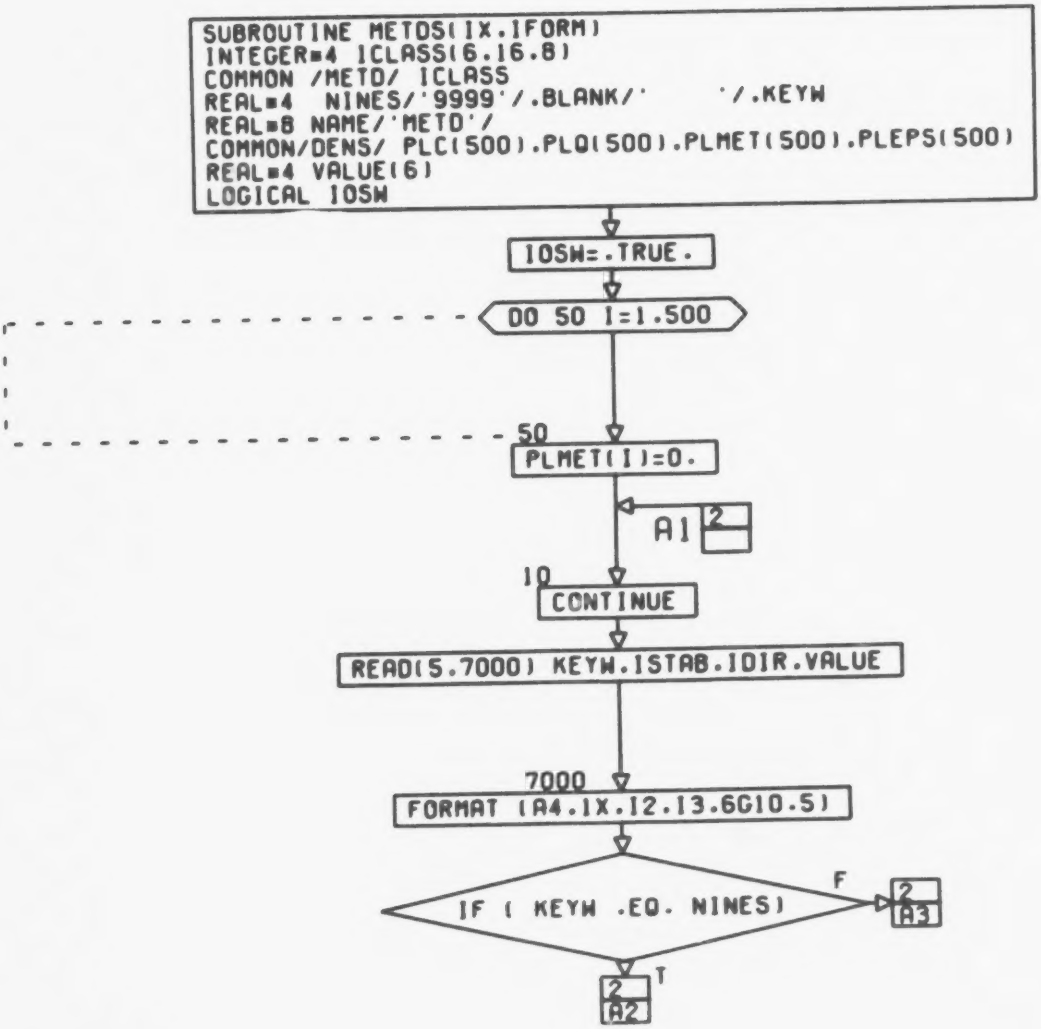
PG 3 OF 4


IF(NOX.GT.NO)
F
T
GO TO 10
1
A1
3
300
CONTINUE
GO TO 250
3
A4
7005
FORMAT (10X.6G10.5)
7015
FORMAT(T11.6(G10.4.10X))
2
A5
1000
RETURN
END

PG 4 FINAL

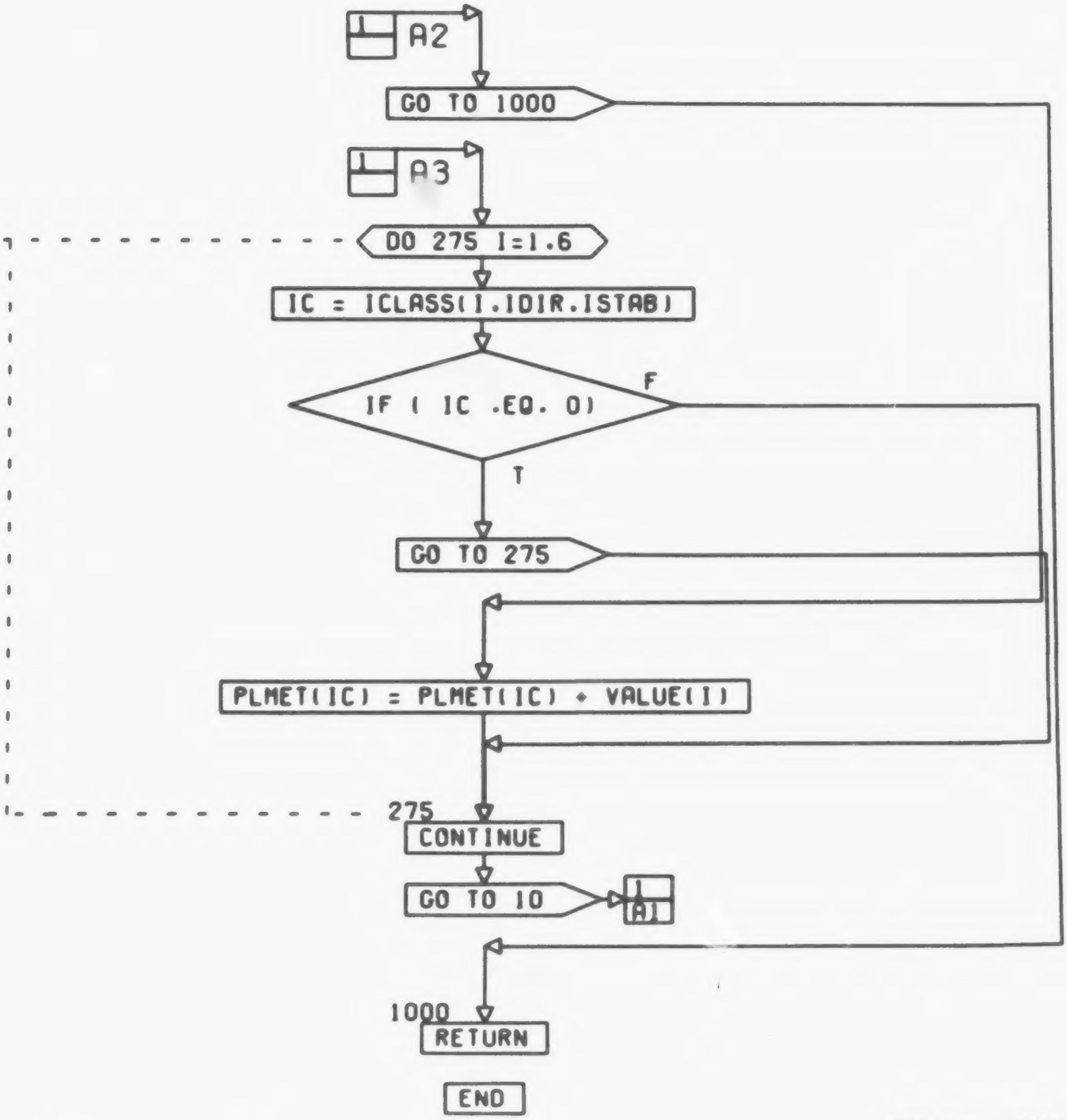

SUBROUTINE COMP(IC.IFORM)
RETURN
END

PG 1 FINAL

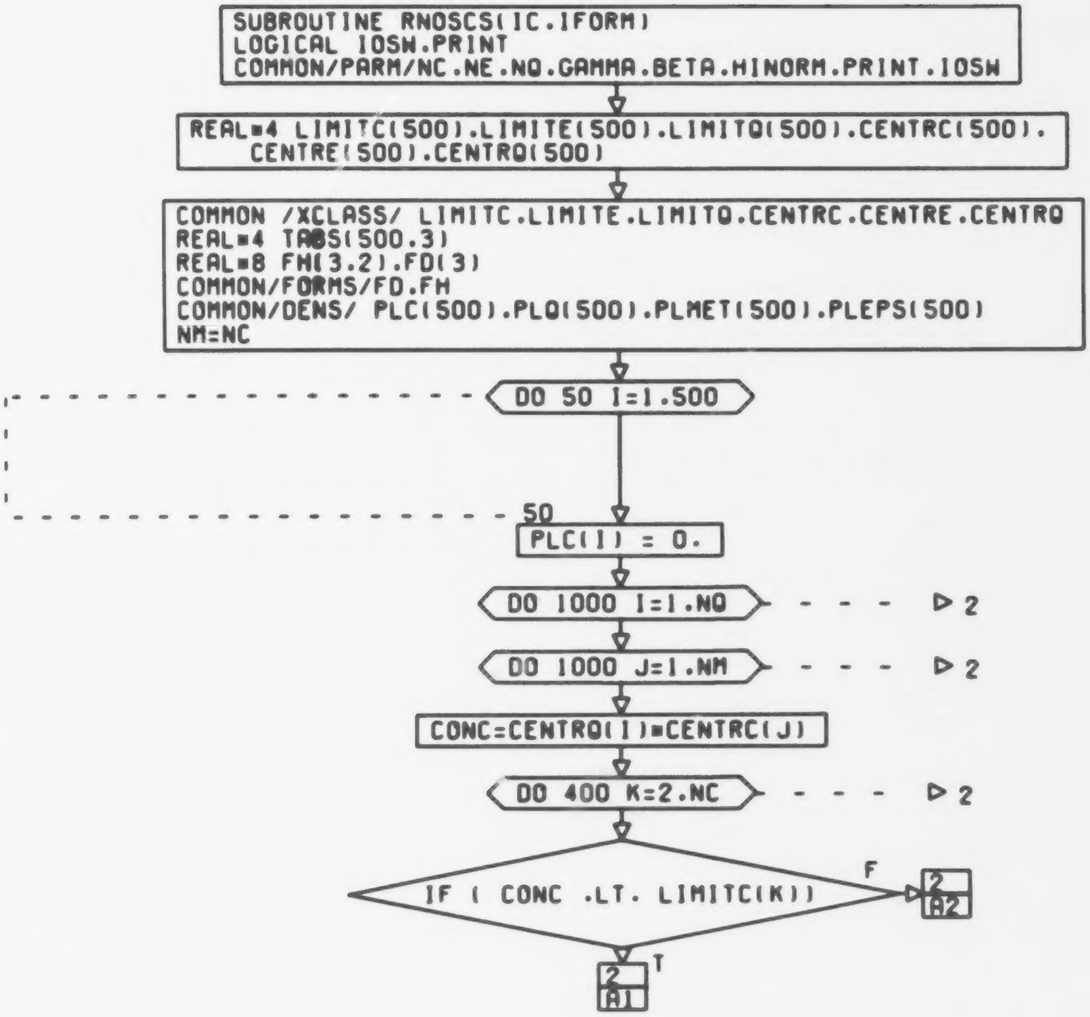


```
SUBROUTINE METDS(IX.IFORM)
INTEGER*4 ICLASS(6.16.8)
COMMON /METD/ ICLASS
REAL*4  NINES/'9999'/.BLANK/'    '/.KEYW
REAL*8 NAME/'METD'/
COMMON/DENS/ PLC(500).PLQ(500).PLMET(500).PLEPS(500)
REAL*4 VALUE(6)
LOGICAL IOSW

IOSW=.TRUE.
DO 50 I=1.500
50 PLMET(I)=0.
10 CONTINUE
READ(5.7000) KEYW.ISTAB.IDIR.VALUE
7000 FORMAT (A4.1X.I2.I3.6G10.5)
IF ( KEYW .EQ. NINES)
```

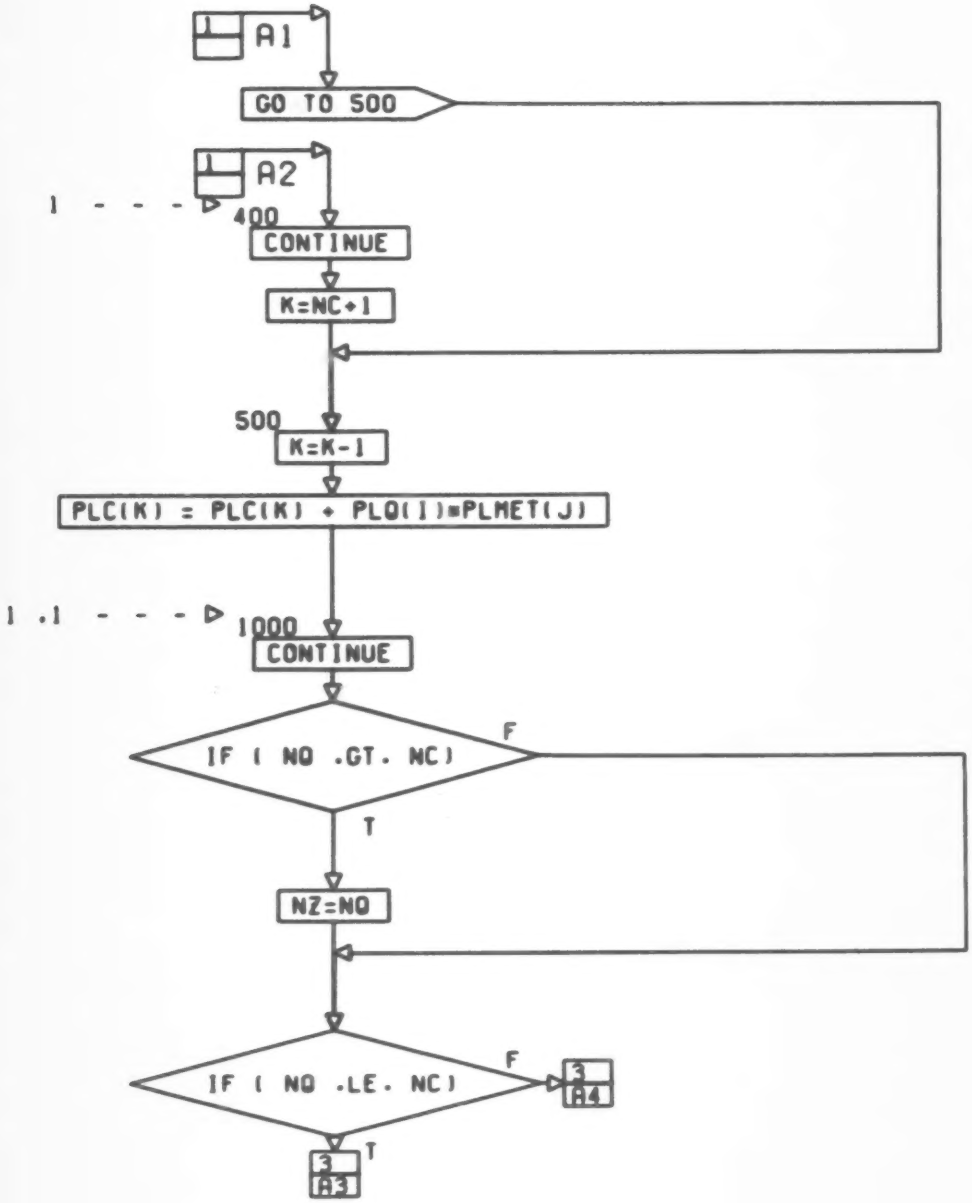
PG 1 OF 2


A2
GO TO 1000
A3
DO 275 I=1.6
IC = ICLASS(I.IDIR.ISTAB)
IF (IC .EQ. 0)
F
T
GO TO 275
PLMET(IC) = PLMET(IC) + VALUE(I)
275
CONTINUE
GO TO 10
A1
1000
RETURN
END

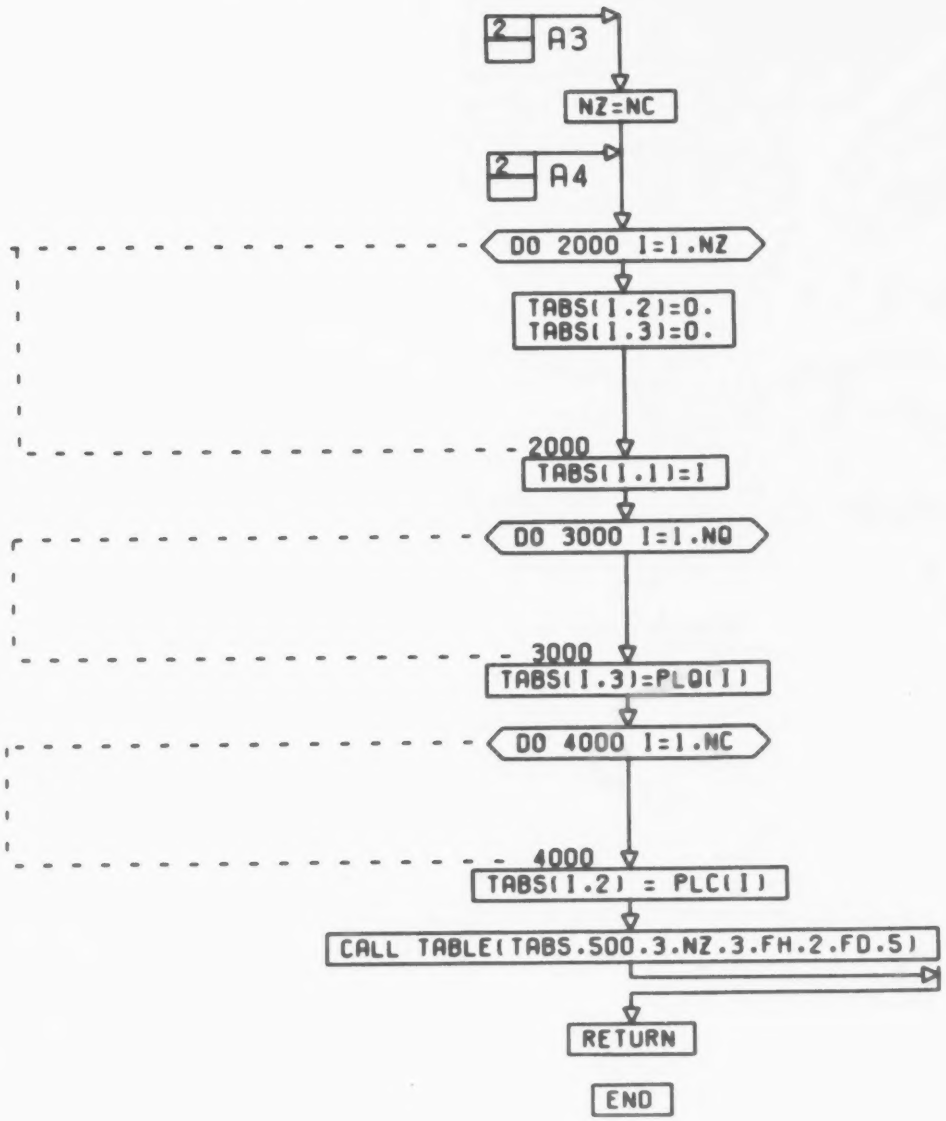
PG 2 FINAL



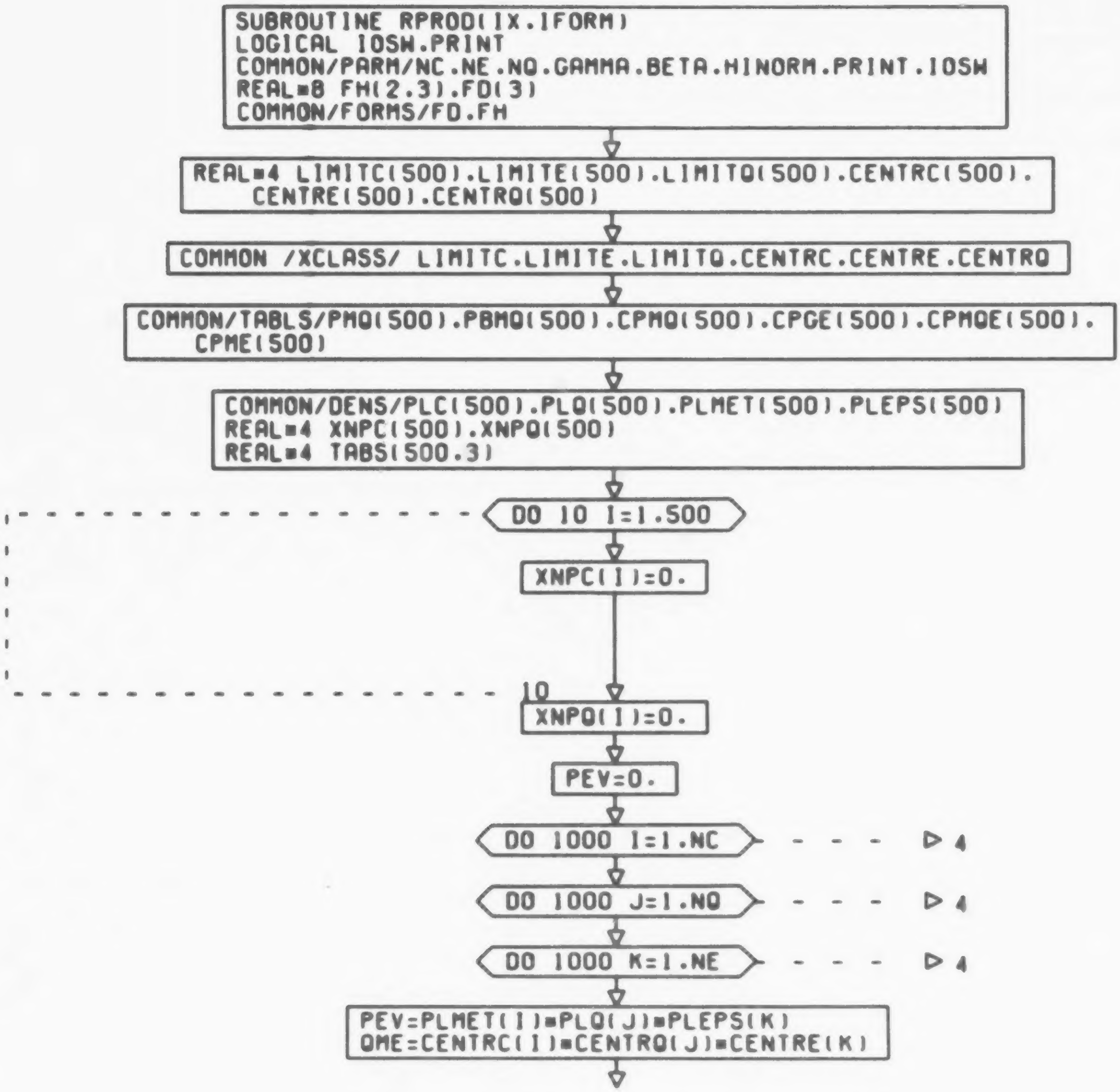
```
SUBROUTINE RNOSCS(IC.IFORM)
LOGICAL IOSW.PRINT
COMMON/PARM/NC.NE.NQ.GAMMA.BETA.MINORM.PRINT.IOSW
REAL*4 LIMITC(500).LIMITE(500).LIMITQ(500).CENTRC(500).
    CENTRE(500).CENTRQ(500)
COMMON /XCLASS/ LIMITC.LIMITE.LIMITQ.CENTRC.CENTRE.CENTRQ
REAL*4 TABS(500.3)
REAL*8 FM(3.2).FD(3)
COMMON/FORMS/FD.FM
COMMON/DENS/ PLC(500).PLQ(500).PLMET(500).PLEPS(500)
NM=NC
DO 50 I=1.500
50 PLC(I) = 0.
DO 1000 I=1.NQ
DO 1000 J=1.NM
CONC=CENTRQ(I)*CENTRC(J)
DO 400 K=2.NC
IF ( CONC .LT. LIMITC(K))
```


1
A1
GO TO 500
1
A2
1 - - - ▷ 400
CONTINUE
K=NC+1
500
K=K-1
PLC(K) = PLC(K) + PLQ(I)*PLMET(J)
1 .1 - - - ▷ 1000
CONTINUE
IF (NO .GT. NC)
F
T
NZ=NO
IF (NO .LE. NC)
F
3
A4
T
3
A3

PG 2 OF 3

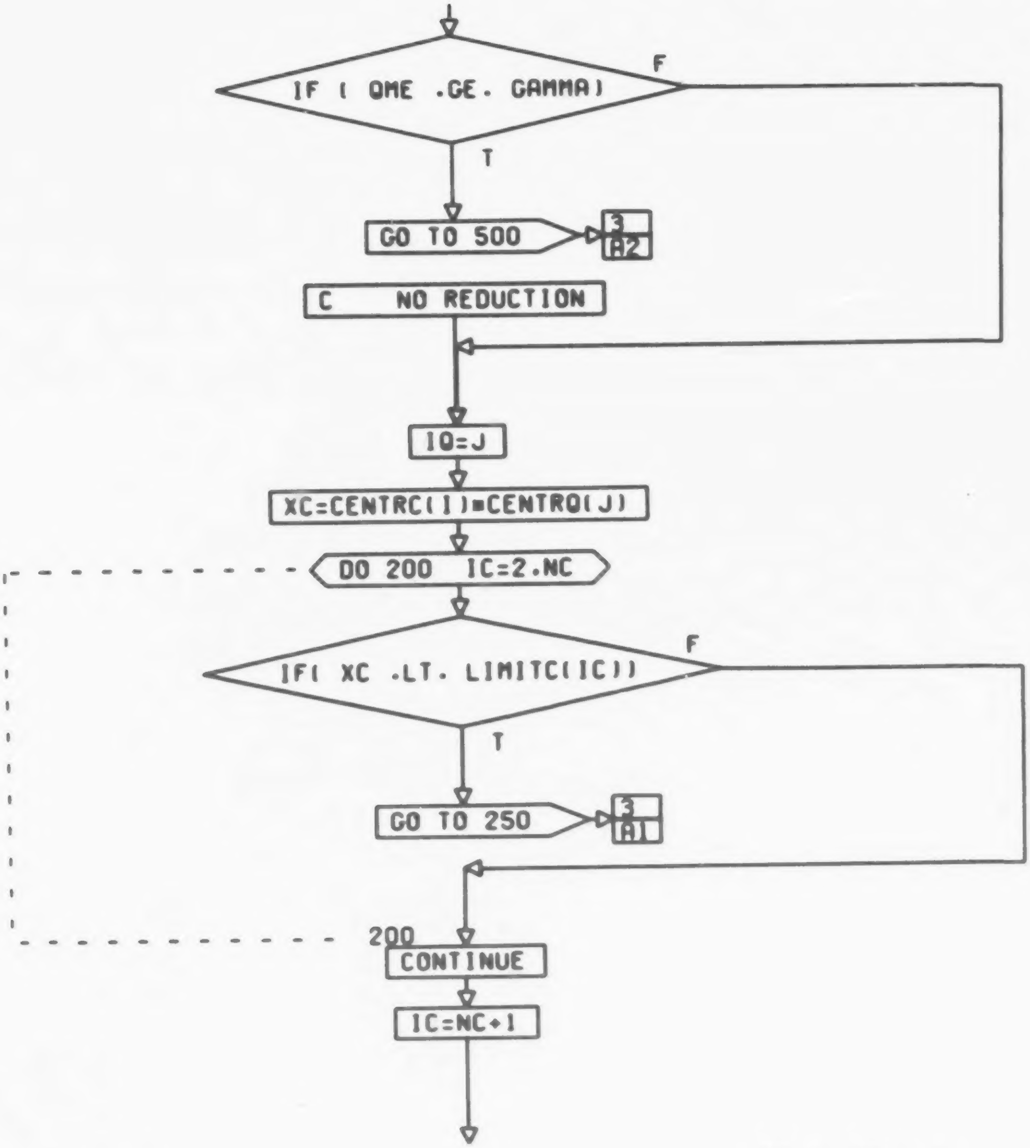

2
A3
NZ=NC
2
A4
DO 2000 I=1.NZ
TABS(I.2)=0.
TABS(I.3)=0.
2000
TABS(I.1)=I
DO 3000 I=1.NQ
3000
TABS(I.3)=PLQ(I)
DO 4000 I=1.NC
4000
TABS(I.2) = PLC(I)
CALL TABLE(TABS.500.3.NZ.3.FH.2.FD.5)
RETURN
END

PG 3 FINAL

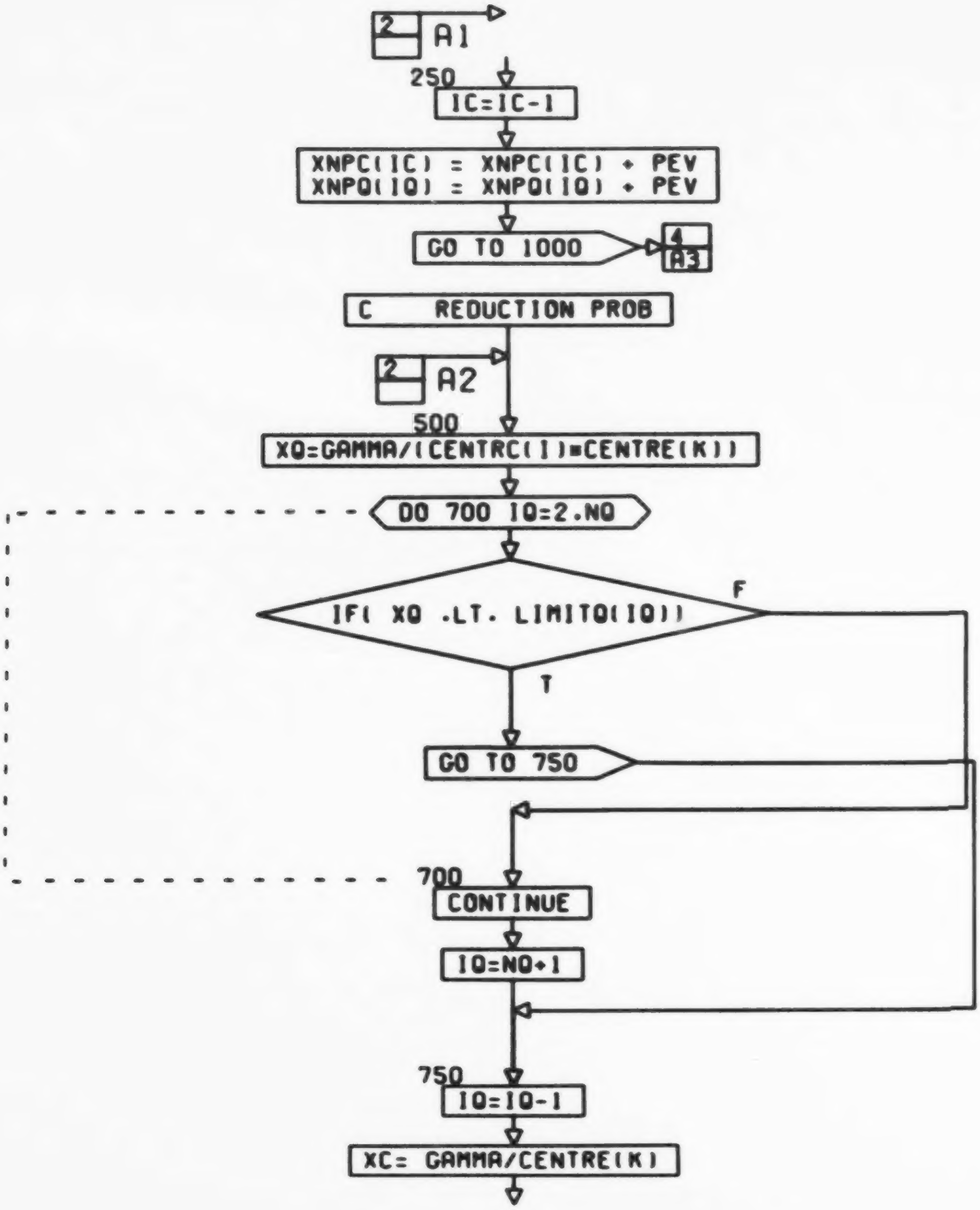


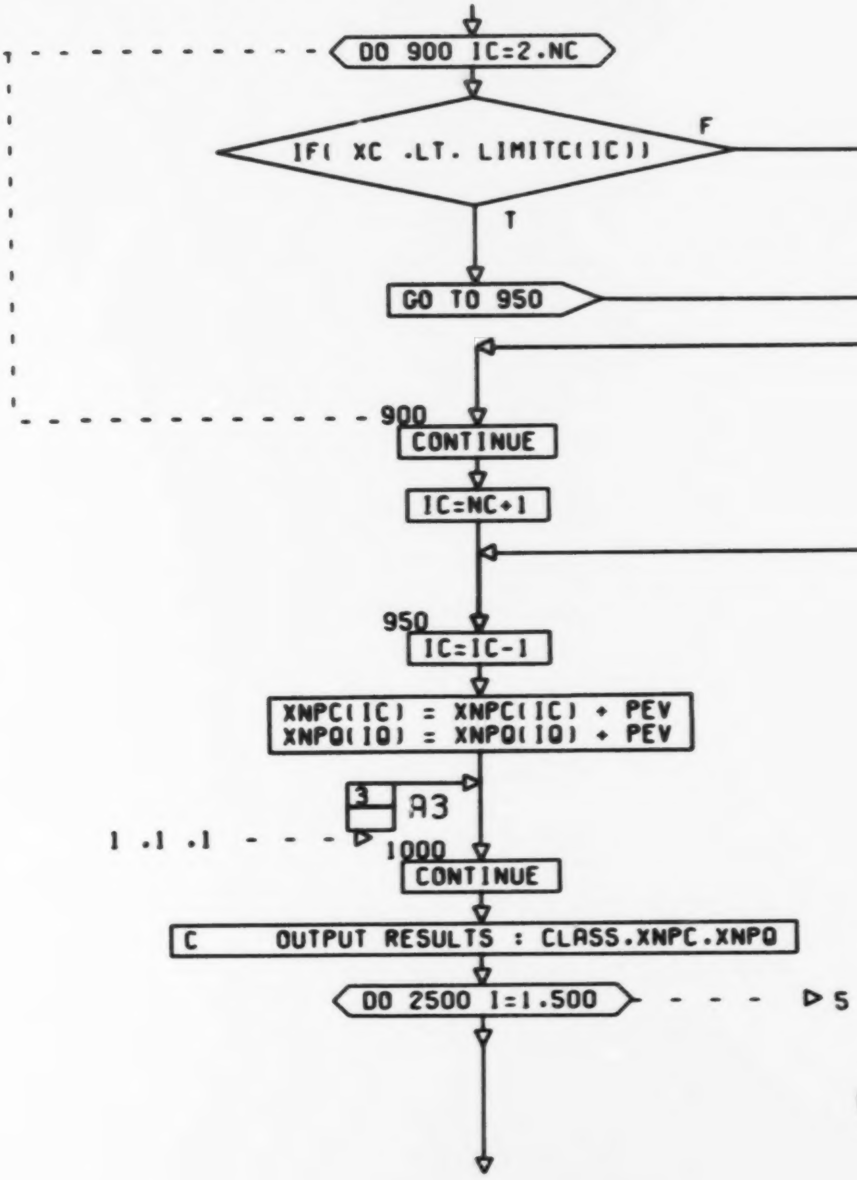
```
SUBROUTINE RPROD(IX.IFORM)
LOGICAL IOSW.PRINT
COMMON/PARM/NC.NE.NQ.GAMMA.BETA.HINORM.PRINT.IOSW
REAL*8 FH(2.3).FD(3)
COMMON/FORMS/FD.FH

REAL*4 LIMITC(500).LIMITE(500).LIMITQ(500).CENTRC(500).
    CENTRE(500).CENTRQ(500)

COMMON /XCLASS/ LIMITC.LIMITE.LIMITQ.CENTRC.CENTRE.CENTRQ

COMMON/TABLS/PMQ(500).PBMQ(500).CPMQ(500).CPGE(500).CPMQE(500).
    CPME(500)

COMMON/DENS/PLC(500).PLQ(500).PLMET(500).PLEPS(500)
REAL*4 XNPC(500).XNPQ(500)
REAL*4 TABS(500.3)

DO 10 I=1.500

XNPC(I)=0.

10 XNPQ(I)=0.

PEV=0.

DO 1000 I=1.NC

DO 1000 J=1.NQ

DO 1000 K=1.NE

PEV=PLMET(I)*PLQ(J)*PLEPS(K)
QME=CENTRC(I)*CENTRQ(J)*CENTRE(K)
```

PG 1 OF 7

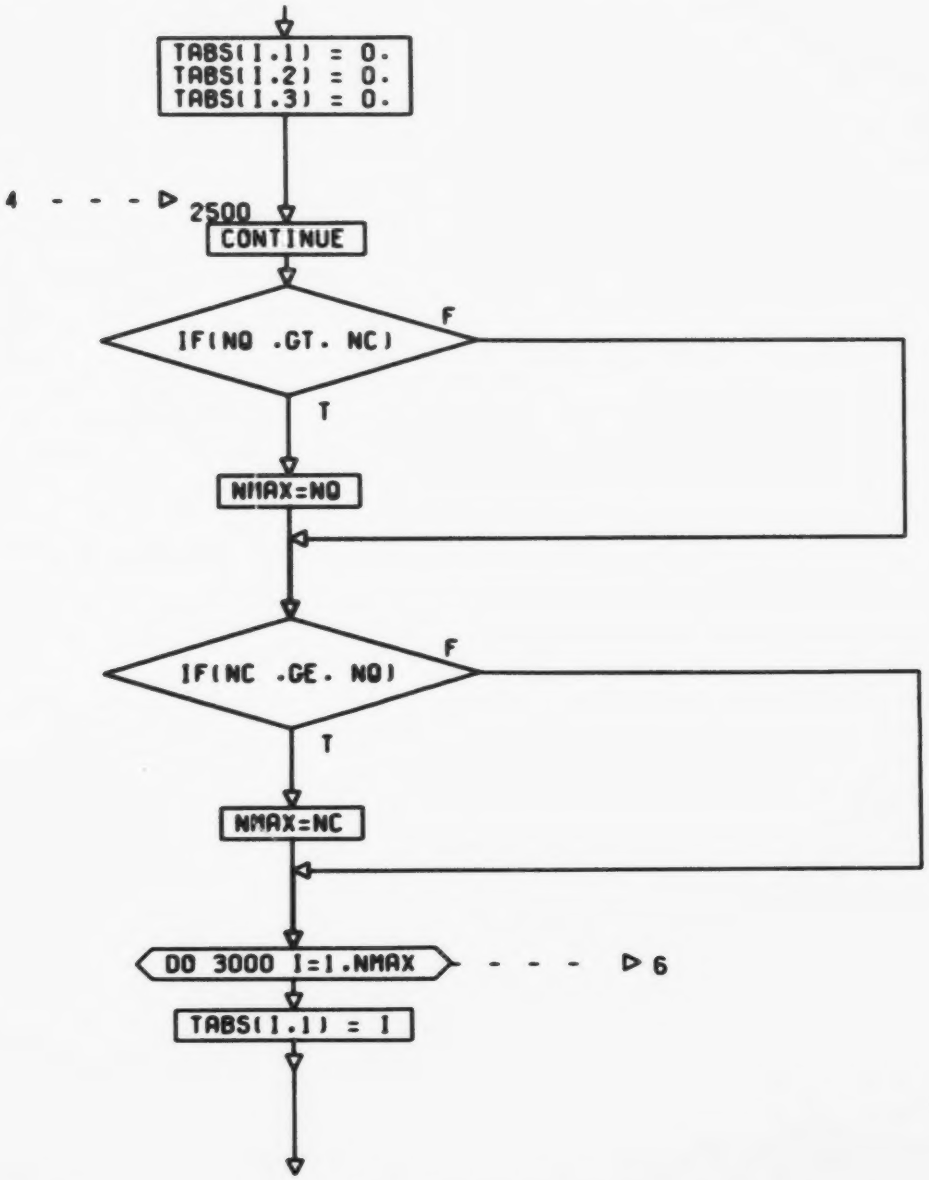

IF (QME .GE. GAMMA)
F
T
GO TO 500
3
A2
C NO REDUCTION
IQ=J
XC=CENTRC(I)*CENTRQ(J)
DO 200 IC=2.NC
IF(XC .LT. LIMITC(IC))
F
T
GO TO 250
3
A1
200
CONTINUE
IC=NC+1

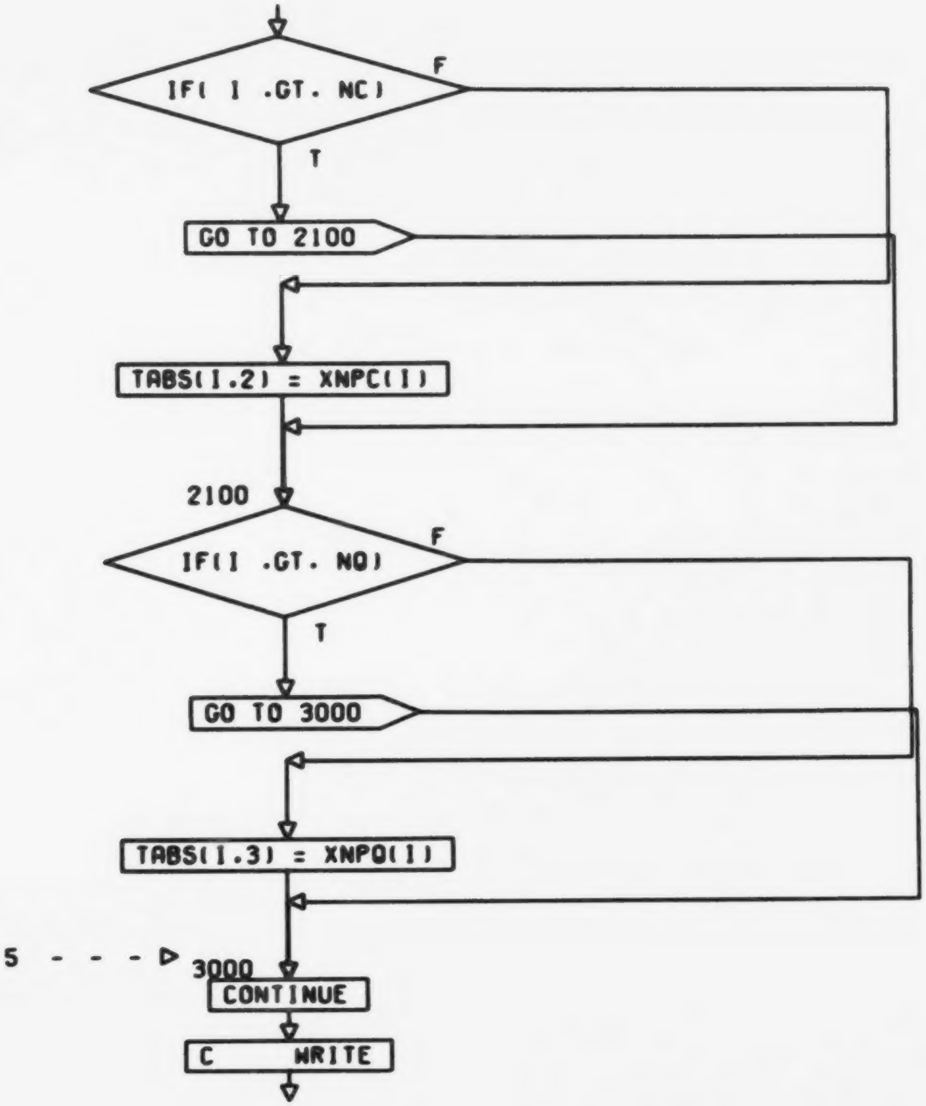
PG 2 OF 7


2
A1
250
IC=IC-1
XNPC(IC) = XNPC(IC) + PEV
XNPQ(IQ) = XNPQ(IQ) + PEV
GO TO 1000
4
A3
C REDUCTION PROB
2
A2
500
XQ=GAMMA/(CENTRC(I)*CENTRE(K))
DO 700 IQ=2.NQ
IF(XQ .LT. LIMITQ(IQ))
F
T
GO TO 750
700
CONTINUE
IQ=NQ+1
750
IQ=IQ-1
XC= GAMMA/CENTRE(K)

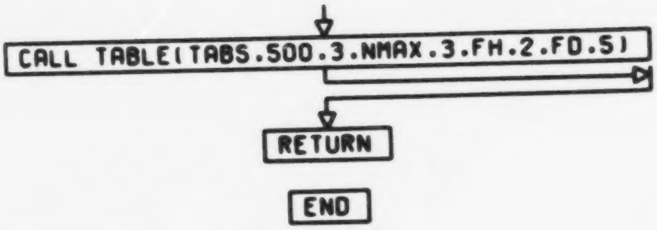

DO 900 IC=2.NC
IF(XC .LT. LIMITC(IC))
F
T
GO TO 950
900
CONTINUE
IC=NC+1
950
IC=IC-1
XNPC(IC) = XNPC(IC) + PEV
XNPO(IO) = XNPO(IO) + PEV
3
A3
1 .1 .1
1000
CONTINUE
C OUTPUT RESULTS : CLASS.XNPC.XNPO
DO 2500 I=1.500
5

PG 4 OF 7


TABS(I.1) = 0.
TABS(I.2) = 0.
TABS(I.3) = 0.
4
2500
CONTINUE
IF(NO .GT. NC)
F
T
NMAX=NO
IF(NC .GE. NO)
F
T
NMAX=NC
DO 3000 I=1.NMAX
6
TABS(I.1) = I


IF(I .GT. NC)
F
T
GO TO 2100
TABS(I.2) = XNPC(I)
2100
IF(I .GT. NO)
F
T
GO TO 3000
TABS(I.3) = XNPO(I)
5
3000
CONTINUE
C WRITE

PG 6 OF 7



```
CALL TABLE(TABS.500.3.NMAX.3.FH.2.FD.5)
RETURN
END
```

PG 7 FINAL

APPENDIX C

SAMPLE CASES OF PROBL

The following examples have been taken from the original study (EPA 1976a) and isolate the effect of changes in each of the pertinent variables which influence reliability. These variables include: $\overline{R}$, the geometric mean of the error ratio R; σ, the standard deviation of the error ratio distribution; γ, the threshold value of the predicted maximum concentration above which some operational process adjustment is made; and β, the ratio of the sulfur content of the low sulfur fuel to the sulfur content of the high sulfur fuel used in a fuel switch SCS.

Example 1 - What is the effect on SCS reliability of changing the value of σ for the error ratio R?

Reduction of the value of σ for the Error Ratio R is a desirable objective of every SCS operation. If σ could be made negligibly small, the SCS could be perfectly reliable with a minimum loss of production or fuel costs for the source. A nonzero value of σ results from the presence of unbiased errors in meteorological forecasting, estimation of emissions, or modeling results. A reduction in σ would be expected from any of the following system improvements.

- Additional or improved meteorological data used in predicting the meteorological parameters which are input for air quality forecasts. Unless R_w is very near 1.0 or the system is operating near the predictability limit for each parameter, some improvement through added meteorological support might be atmospheric sounding data, on-site wind measurements, NWS teletype or facsimile circuits, a wind field generator model, a faster data reduction system, or simply more frequent observations of important meteorological data.
- More experienced or more capable meteorological personnel. Because personnel gain experience as the system is operated, the σ of the system should become smaller with time.

- An improved model. As a forecasting model is updated through system experience, a reduction in σ is to be expected.
- An improved emission schedule forecast system. This improvement might be gained by more thorough production planning or it might involve more careful fuel or materials analysis, better emissions monitoring, or better plant process monitoring.

Table 1-1 summarizes the results of this sample analysis. Note that all SCS operating parameters are the same for each SCS option except that σ is varied. The first column in the summary table describes the six SCS options and the NO SCS option (for comparison). The second column contains the frequency of violations of a 1-hour standard of 0.5 ppm expected to occur with the indicated control strategy. The third column contains the fraction of low cost fuel (higher sulfur content) which can be used. The remaining fraction of fuel must be more expensive (lower sulfur content) fuel. The fourth column contains the fraction of the time that full production is possible assuming that the SCS process curtailment is the only constraint.

Clearly, any of the six SCS plans reduces the frequency of violations by at least a factor of 2 but, interestingly, no more than a factor of 3.4. By improving forecast accuracy for the fuel switching cases, SCS reliability is noticeably improved. Since the fuel switching constant $\beta = 0.25$ is overly conservative in most cases, nearly every switch action results in concentrations below standards. Therefore, improved accuracy of prediction (reduced σ) results in fewer potential violations escaping control. Since the switch threshold $\gamma = 0.5$ is exactly the standard, there is no conservatism in the process curtailment forecasts. Although improved forecast accuracy reduces the magnitude of violating concentrations, the number of violations remains the same. These examples indicate that some conservatism is desirable for an efficient SCS strategy. Ways of including conservatism are discussed later.

Improved forecast accuracy can have possible economic and social benefits despite the probable added expense. For the fuel switching examples, use of valuable low sulfur fuel is reduced from 0.25 to 0.23, and finally to 0.19 of the total fuel used as forecasting accuracy is improved. Meanwhile, SCS reliability is also improved. Note that full

TABLE 1-1

EFFECTS ON SCS RELIABILITY OF CHANGING THE VALUE OF σ FOR THE ERROR RATIO R

Each SCS plan below has the following parameter values:

Fuel switching fraction $\beta = 0.25$
Switching threshold $\gamma = 0.5$
Geometric Mean of Error Ratio $\overline{R} = 1.0$
Width of Error Ratio distribution σ is variable

SCS Control Strategy	Total Frequency of Violations	Fraction of Low Cost Fuel	Fraction of Time at Full Production
NO SCS	0.16432	1.000	1.000
SCS #1 FUEL SWITCHING $\sigma = 0.5$	0.06605	0.754	1.000
SCS #2 FUEL SWITCHING $\sigma = 0.4$	0.06291	0.768	1.000
SCS #3 FUEL SWITCHING $\sigma = 0.2$	0.04875	0.808	1.000
SCS #4 PROCESS CURTAILMENT $\sigma = 0.5$	0.08194	1.000	0.918
SCS #5 PROCESS CURTAILMENT $\sigma = 0.4$	0.08216	1.000	0.948
SCS #6 PROCESS CURTAILMENT $\sigma = 0.2$	0.08216	1.000	0.961

production is assumed to be possible regardless of fuel type. For the process curtailment cases, the percentage of full production is increased as forecast accuracy improves. Meanwhile, SCS reliability is maintained at the same level.

Example 2 - What is the effect on SCS reliability of changing the value of $\overline{R}$ for the error ratio R?

The geometric value of the error ratio, $\overline{R}$, is less than 1.0 if concentrations are characteristically underpredicted, greater than 1.0 if concentrations are characteristically overpredicted, and 1.0 if there is no systematic bias in prediction. It is easy for a system to achieve a value of $\overline{R} = 1.0$ by simply reducing each forecast value by the required amount to bring the mean of past values to 1.0. It is generally desirable, however, to intentionally operate an SCS conservatively to prevent a high frequency of violations which are near but higher than the standard. The limits on reliability of a nonconservative SCS were illustrated in the previous example analysis. One method of operating a conservative SCS is to maintain an error ratio mean $\overline{R}$ greater than 1.0.

An air quality forecast model which overpredicts provides a means of achieving $\overline{R}$ greater than 1.0. Most air quality models overpredict because "worst-case" conditions such as persistent meteorology and conservative plume rise are assumed.

Similarly, meteorological and emission predictions used for air quality projections are often chosen to be "worst-case" forecasts. For example, predicting fumigation conditions for all clear mornings would produce a value of $\overline{R}$ greater than 1.0, but may be necessary to prevent contravention of standards on those several mornings when inversion breakup is a problem.

The sample analysis that follows is designed to investigate the effect of changing $\overline{R}$ on SCS reliability, leaving all other SCS parameters unchanged. Table 1-2 includes the results of the operation of six hypothetical SCS schemes and the NO SCS case.

TABLE 1-2

EFFECTS ON SCS RELIABILITY OF CHANGING THE VALUE OF $\overline{R}$ FOR THE ERROR RATIO R

Each SCS plan below has the following parameter values:

Fuel switching fraction = β = 0.25
Switching threshold = γ = 0.5
Geometric mean of error ratio $\overline{R}$ is variable
Width of error ratio distribution σ = 0.5

SCS Control Strategy	Total Frequency of Violations	Fraction of Low Cost Fuel	Fraction of Full Production
NO SCS	0.16432	1.000	1.000
SCS #1 FUEL SWITCHING $\overline{R}$ = 1.0	0.06606	0.754	1.000
SCS #7 FUEL SWITCHING $\overline{R}$ = 1.5	0.00876	0.521	1.000
SCS #8 FUEL SWITCHING $\overline{R}$ = 2.0	0.00370	0.413	1.000
SCS #2 PROCESS CURTAILMENT $\overline{R}$ = 1.0	0.08194	1.000	0.918
SCS #9 PROCESS CURTAILMENT $\overline{R}$ = 1.5	0.01306	1.000	0.836
SCS #10 PROCESS CURTAILMENT $\overline{R}$ = 2.0	0.00000	1.000	0.609

Again, each of the six SCS plans reduces the frequency of violations by a considerable amount. The increased conservatism of air quality prediction, manifested in increased values of $\overline{R}$, reduces the frequency of violations of the standard for both fuel switching and process curtailment. For fuel switching, 43 of every 44 violations can be eliminated using an SCS with $\overline{R} = 2.0$.

The economic penalty for the indicated improvements in air quality is shown in the final two columns of Table 1-2. With $\overline{R} = 2.0$, lower sulfur fuel is required 59% of the time for operation of the fuel-switching plan. For process curtailment, a negligible violation frequency is accomplished by reducing maximum possible production by 39%. Unlike reducing σ, increasing $\overline{R}$ above 1.0 has no compensating economic savings.

Example 3 - What is the effect on SCS reliability of changing the value of the switch threshold γ ?

The previous sample analysis investigated the improvement in SCS reliability effected by conservative air quality forecasting. Another method of improving SCS reliability is through the use of a switch threshold less than the standard. Similar to making conservative predictions, this control technique compensates for tendencies to underpredict since most underprediction errors will result in "violations" of the threshold which are still below the standard.

Table 1-3 displays the results of the sample analysis for six hypothetical SCS plans with switch thresholds of varying values.

Systematic improvement in SCS reliability is evident for both the fuel-switching cases and the process-curtailment cases as the switch threshold is made a smaller fraction of the air quality standard.

Systematic reduction in economic benefit manifested in fractional fuel usage data and fraction of full production data is also evident. Similar to maintaining the value of $\overline{R}$ greater than 1.0, a conservative switch threshold is a simple tool for improving SCS reliability; an overall loss of plant efficiency is a probable effect of the control strategy.

TABLE 1-3

EFFECTS ON SCS RELIABILITY OF CHANGING THE VALUE OF THE SWITCH THRESHOLD γ

Each SCS plan below has the following parameter values:

Fuel Switching Fraction $\beta = 0.25$
Switching Threshold γ is variable
Geometric Mean of Error Ratio $\overline{R} = 1.0$
Width of Error Ratio Distribution $\sigma = 0.5$

SCS Control Strategy	Total Frequency of Violations	Fraction of Low Cost Fuel	Fraction of Full Production
No SCS	0.16432	1.000	1.000
SCS #1 Fuel Switching $\gamma = 0.5$	0.06606	0.754	1.000
SCS #11 Fuel Switching $\gamma = 0.4$	0.03500	0.615	1.000
SCS #12 Fuel Switching $\gamma = 0.3$	0.01562	0.526	1.000
SCS #2 Process Curtailment $\gamma = 0.5$	0.08194	1.000	0.918
SCS #13 Process Curtailment $\gamma = 0.4$	0.05641	1.000	0.873
SCS #14 Process Curtailment $\gamma = 0.3$	0.02557	1.000	0.801

Example 4 - What is the effect on SCS reliability of changing the fuel switching fraction β?

Although choice of a fuel switching fraction β is most likely determined by the availability of fuel types, it is interesting to observe the effect of changing the value of β. One can hypothetically achieve any value of β by blending fuels of known sulfur content, but engineering problems prohibit this generality in most cases.

Three SCS plans with values of β of 0.25, 0.30, and 0.40 were investigated. No appreciable change in SCS reliability or in plant production was observed. Apparently, the value β used in all three cases is very conservative; that is, each time a switch is implemented to a lower sulfur content fuel a greater than necessary reduction in concentrations is achieved. Therefore, increasing the value of β toward 1.0 has no effect on violation frequency for values of β less than 0.5.

Example 5 - What is the effect on SCS reliability of maintaining a conservative value of $\overline{R}$ for the error ratio R and changing the value of γ?

The preceding examples indicate that significant improvement in air quality can be expected from any one of many reliable SCS plans. It is not possible to define which SCS is both sufficiently reliable for acceptance by control agencies and economically practical for acceptance by plant operators. It is likely that some combination of the preceding sample SCS systems would be optimum for most operations.

Furthermore, it is conceivable that an operating SCS will require updating due to demands for more SCS reliability or due to demands for more cost-effective operation by the plant management. In this eventuality, it is likely that some combination of the preceding SCS changes would be optimum for the particular operation.

It is, therefore, important and interesting to observe the effects of more than one parameter change on SCS reliability. Table 1-4 includes six sample SCS plans that observe the effects of changing the switch threshold γ and employing a conservative mean value of the Error Ratio R.

TABLE 1-4

EFFECTS ON SCS RELIABILITY OF OPERATING WITH A CONSERVATIVE VALUE OF $\overline{R}$ AND CHANGING γ

Each SCS plan below has the following parameter values:

Fuel Switching Fraction $\beta = 0.25$
Switching Threshold γ is variable
Geometric Mean of Error Ratio $\overline{R} = 1.5$
Width of Error Ratio Distribution $\sigma = 0.5$

SCS Control Strategy	Total Frequency of Violations	Fraction of Low Cost Fuel	Fraction of Full Production
No SCS	0.16432	1.000	1.000
SCS #15 Fuel Switching $\gamma = 0.4$	0.00471	0.450	1.000
SCS #16 Fuel Switching $\gamma = 0.3$	0.00370	0.395	1.000
SCS #17 Fuel Switching $\gamma = 0.2$	0.00370	0.372	1.000
SCS #18 Process Curtailment $\gamma = 0.4$	0.00353	1.000	0.784
SCS #19 Process Curtailment $\gamma = 0.3$	0.00000	1.000	0.664
SCS #20 Process Curtailment $\gamma = 0.2$	0.00000	1.000	0.572

Comparing SCS Number 7 and the three fuel-switching plans in Table 1-4, it is clear that increased conservatism yields only small improvement in reliability until the SCS reaches its limit of reliability under the fuel-switching plan. Further improvement would require the plant to cease operations 0.37% of the time, or 32 hours per year. For process curtailment a comparison of SCS Number 9 and the three plans included in Table 1-4 indicate continuous improvement in SCS reliability with decreasing value of the switch threshold. Values of γ less than 0.3 are unnecessary since only a negligible frequency of violations is expected at a value of $\gamma = 0.3$.

Note that SCS Number 19 expects less than 0.1 violations per year and achieves more than 66% of full production. Considering no other complexities in evaluating SCS reliability, SCS Number 19 accomplishes most acceptable reliability with maximum plant production of all SCS plans considered in these examples.

Example 6 - How can emission error be incorporated into the analysis?

Each of the sample analyses considered so far in this section considers the error ratio R to be some hypothetical log-normally distributed function. No attempt has been made to simulate the effects of each component of SCS reliability. The following sample analysis will consider SCS schemes that have meteorological error distributed like the Error Ratios of the preceding examples, but that also have emission errors. According to the discussion in Section 3,

$$R = R_W \cdot R_Q \cdot R_M$$

For these examples, we assume $R_M = 1.0$, therefore

$$R = R_W \cdot R_Q$$

We will assume that R_W has a log-normal distribution with $\overline{R}_W = 1.0$ and $\sigma_W = 0.5$. Furthermore, we will assume that

$$R_Q = \frac{Q_p}{Q_o} \;;$$

that is, that the error in emission rate Q is measured simply by the ratio of predicted Q to the observed Q for that time.

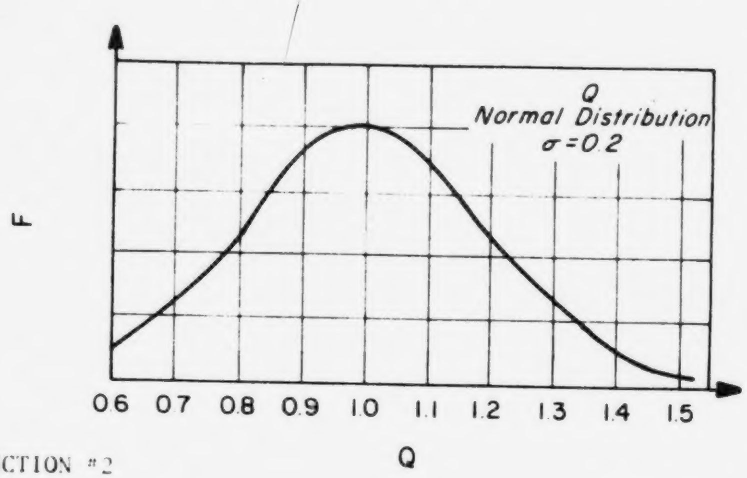
Then,

$$R = \frac{Q_p}{Q_o} R_W$$

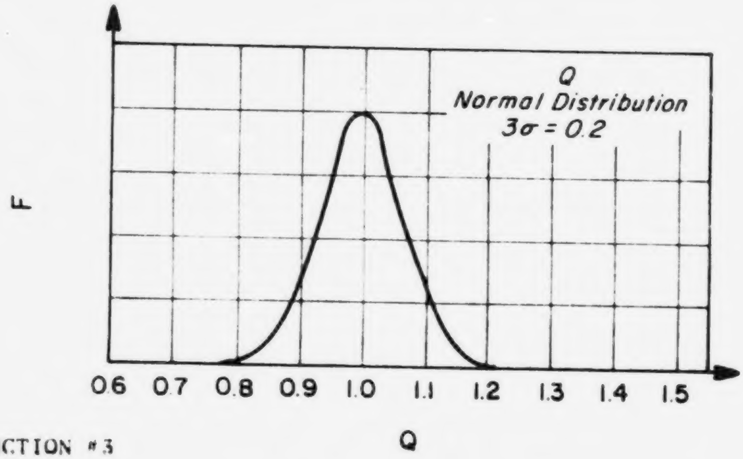
It is reasonable to expect that $\frac{Q_p}{Q_o}$ has either a normal or a "top-hat" distribution. The example below considers both of these possibilities. The hypothesized distributions for R_W and R_Q are combined to form a distribution for R. Figure 1-1 illustrates the three distributions of $\frac{Q_p}{Q_o}$ used. They are designated as Q functions 1, 2 and 3.

Table 1-5 summarizes the results of the analysis using the combined Error Ratios. The frequency of violations for all six sample SCS plans is greater than the frequency of violations for the corresponding SCS with no emissions error (SCS Number 1 or SCS Number 2). Improvement in SCS reliability is achieved as σ of the distribution is reduced. The "top-hat" emission error distribution is associated with a reliability intermediate between the two normally distributed emission error functions.

Q FUNCTION #1



Q FUNCTION #2



Q FUNCTION #3

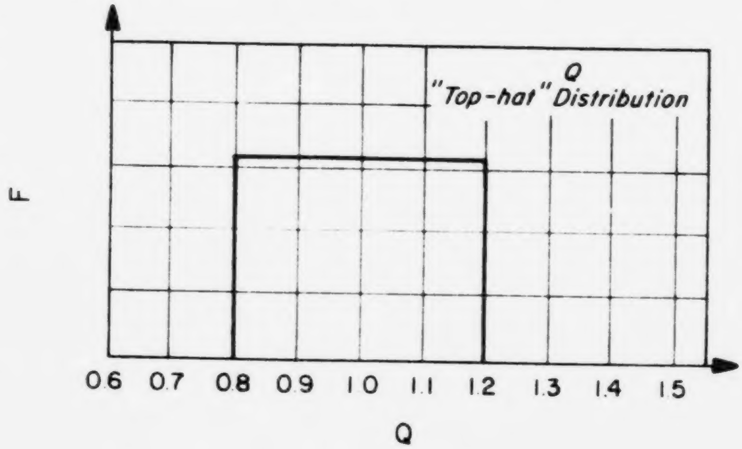


Figure 1-1 Three Frequency Distributions of Ratio Q_p/Q_o

TABLE 1-5

INCORPORATION OF EMISSIONS ERROR INTO THE RELIABILITY ANALYSIS

Each SCS plan below has the following parameter values:

Fuel Switching Fraction $\beta = 0.25$
Switching Threshold $\gamma = 0.5$
Geometric Mean of Error Ratio $\overline{R} = 1.0$
Width of Error Ratio $\sigma = 0.5$

SCS Control Strategy	Total Frequency of Violations	Fraction of Low Cost Fuel	Fraction of Full Production
No SCS	0.16432	1.000	1.000
SCS #21 Fuel Switching Q Error 1	0.07079	0.765	1.000
SCS #22 Fuel Switching Q Error 2	0.06837	0.764	1.000
SCS #23 Fuel Switching Q Error 3	0.06943	0.766	1.000
SCS #24 Process Curtailment Q Error 1	0.08582	1.000	0.920
SCS #25 Process Curtailment Q Error 2	0.08397	1.000	0.921
SCS #26 Process Curtailment Q Error 3	0.08523	1.000	0.921

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16. ABSTRACT

Through a supplementary control system (SCS), SO_2 emissions from a facility are temporarily curtailed when meteorological conditions conducive to high ambient SO_2 concentrations exist or are anticipated. This report describes a case study demonstration of SCS reliability analysis techniques presented in "Technique for Supplementary Control System Reliability Analysis and Upgrading" (EPA-450/2-76-015). A user manual is also provided. A primary objective of this study is to discuss the reliability analysis techniques and their applicability to the problem of estimating SCS reliability.

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